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FINAL REPORT

Use of Prepump Separation Technologies to Enhance Cost-Effectiveness of Bioslurper Systems – Long-Term Demonstration

by

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14. ABSTRACT

This report is for ESTCP Project CU-9908. The project demonstrated and validated two innovative prepump modifications to a conventional bioslurper system: an in-well "dual drop tube" extraction system and a modified aboveground knockout tank design. These modifications are meant to reduce operation and maintenance costs associated with the simultaneous extraction of fuel with groundwater by a conventional system, which utilizes a single drop tube in-well vacuum extraction system without a prepump knockout tank. The "dual drop tube" consists of two in-well vacuum drop tubes separated by a fuel isolation sleeve, which extends 1 to 3 feet both above and below the end of the main drop tube. This tubular sleeve prevents the extraction of fuel by the main drop tube, while allowing groundwater and soil gas to enter. A smaller vacuum drop tube, located outside the sleeve, is used to remove accumulating fuel separately, using the bioslurper system pump vacuum and a separate storage vessel. Conventional systems promote extensive emulsification of fuel with groundwater and foam formation resulting from fuel-water mixtures moving through the vacuum manifold system and liquid ring vacuum pump. The "dual drop tube" and prepump knockout tank separators were operated both alone and in series at eight field sites (2- to 5-week demonstrations) and cost and performance data were obtained by a long-term demonstration (15 weeks) at NAS Fallon, Nevada. The dual drop tube separator removed all emulsions and foam and 99% of TPH from the vacuum pump discharge. Cost data are included in the report.

15. SUBJECT TERMS

Bioslurping, dual drop tube, remediation, vacuum assisted extraction, LNAPL, removal, fuel removal, two-phase extraction, in-well separation, prepump separation, biodegradation, aerobic

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Acronyms and Abbreviations

3-D	three-dimensional
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
ALS	air/liquid separator
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and total xylenes
cfm	cubic feet per minute
CSS	Coastal System Station
cSt	centistokes
DAF	dissolved air flotation
DDT	dual drop tube
DoD	Department of Defense
EBS	Environmental Baseline Survey
ESTCP	Environmental Security Technology Certification Program
gpm	gallons per minute
HCl	hydrochloric acid
ID	Identification
JP	jet propulsion
LNAPL	light, nonaqueous-phase liquid
LRP	liquid ring pump
MCAS	Marine Corps Air Station
MCBH	Marine Corps Base Hawaii
MDL	method detection limit
MOGAS	motor fuel
NA	not applicable/available
NAAS	Naval Air Auxiliary Station
NAS	Naval Air Station
NAWC	Naval Air Weapons Center
NCBC	Naval Construction Battalion Center
ND	nondetect
NFESC	Naval Facilities Engineering Service Center
NFD	Naval Fuel Depot

NPDES	Nation Pollutant Discharge Elimination System
NS	not sampled
O&M	operation and maintenance
ORNL	Oak Ridge National Laboratory
OWS	oil/water separator
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
POL	petroleum, oils and lubricant
ppbv	parts per billion by volume
ppmv	parts per million by volume
R&D	research and development
RI	remedial investigation
SCAPS	Site Characterization and Analysis Penetrometer System
SCFM	standard cubic feet per minute
SVE	soil vapor extraction
TLPH	total light petroleum hydrocarbons
TPH	total petroleum hydrocarbons
TPH-E	total petroleum hydrocarbons extractable
TPH-P	total petroleum hydrocarbons purgeable
TSS	total suspended solids
U.S. EPA	United States Environmental Protection Agency
USAF	United States Air Force
VOA	volatile organic analysis
VOC	volatile organic compounds

1.0 Introduction

1.1 Background Information

Bioslurping is a demonstrated technology for removing light, nonaqueous-phase liquid (LNAPL) from contaminated aquifers. Bioslurping combines vacuum-assisted LNAPL recovery with bioventing and soil vapor extraction (SVE) to simultaneously recover LNAPL and bioremediate the vadose zone. A conventional bioslurper system withdraws free-phase LNAPL from the water table, groundwater, and soil vapor in a single process stream, using the air lift created by an aboveground liquid ring pump. The recovered LNAPL is separated from the groundwater and may be recycled. The recovered groundwater and soil vapor usually are treated and discharged. Because bioslurping enhances LNAPL recovery in comparison to conventional skimming and pump-drawdown technologies (Place et al., 2001), bioslurping potentially can save the U.S. Department of Defense (DoD) significant funds by reducing the amount of time required to remediate LNAPL-contaminated sites.

At many sites, the operation of the conventional bioslurper technology results in the formation of floating solids and stable emulsions, thereby creating significant water treatment and waste handling problems. The floating solids observed at many bioslurper sites appear as a foamy mass floating at the LNAPL/water interface in an oil/water separator (OWS). The floating solids are a mixture of extracted LNAPL, groundwater, soil gas, and sediment collected as part of the system process stream. The stable emulsions are suspended droplets of petroleum hydrocarbons in groundwater, which give the bioslurper process water a milky appearance. These emulsions may be produced during the mixing action of the liquid ring pump or from the slurping action within extraction wells. The floating solids and emulsions are relatively stable, and reduce the effectiveness of conventional gravity-driven OWSs. The emulsified materials may require costly downstream treatment, making full-scale implementation of bioslurper technology less attractive. In addition, the bioslurping action volatilizes the LNAPL and increases the petroleum hydrocarbon concentrations in the off-gas stream from the system.

Several system modifications have been attempted by Battelle, the U.S. Navy, and/or the U.S. Air Force (USAF) to mitigate the problems associated with the floating solids and emulsions before the extracted mixtures enter the liquid ring pump. The most promising modifications are the use of dual drop tubes for in-well separation of LNAPL from water (i.e., extracting LNAPL and water in two separate streams), and the use of a prepump separator (i.e., an aboveground knockout tank) to separate LNAPL from the liquid stream prior to the entry of the stream into the liquid ring vacuum pump. In addition to reducing the production of emulsions, removal of LNAPL from the process stream before the LNAPL encounters the turbulent conditions in the liquid ring pump reduces the emission of petroleum vapors by the bioslurping process.

1.2 Official DoD Requirement Statement

This technology demonstration addressed the following Navy Environmental Quality Research and Development (R&D) requirements: 1.I.4.m, Improved Remediation of Soils Contaminated with Non-Chlorinated Hydrocarbons; and 1.I.1.e, Improved Remediation of Groundwater Contaminated with Non-Chlorinated Hydrocarbons.

This project addressed these Navy requirements by improving the performance of the bioslurping process. The bioslurping process removes LNAPL (which is a source for long-term groundwater contamination) from near the water table, and remediates vadose zone soils through bioventing and SVE. The prepump separation methods demonstrated in this project improve the operation of the bioslurping process, making it a more attractive remedial option for LNAPL-contaminated DoD sites.

1.3 Objectives of the Demonstration

The goal of this project was to quantify the effectiveness of prepump LNAPL separation methods in controlling effluent emulsion formation and reducing the concentrations of petroleum hydrocarbons in the aqueous and off-gas streams from the bioslurper. The system was operated in both short-term, single-well demonstrations and in a long-term, multiple-well demonstration to generate operational and cost data. Both in-well and aboveground prepump (knockout tank) separation were evaluated during the short-term and long-term demonstrations.

1.4 Regulatory Issues

The cleanup of LNAPL-contaminated sites usually is driven by state or local limits on the LNAPL thickness on the water table and/or by regulations requiring the removal of LNAPL "to the extent practicable" in order to eliminate it as a potential source for groundwater and soil contamination. LNAPL removal also may be governed by human health or ecological risk-based cleanup goals. Conventional bioslurping has been used successfully to remove LNAPL from contaminated sites, and generally is accepted by regulatory agencies as the preferred method of LNAPL removal.

Other regulations that potentially can apply to the use of prepump oil/water separation are contaminant concentrations and contaminant loadings in process water and vapor discharge streams. Applicable discharge limits may be imposed by Base or municipal wastewater treatment plants, National Pollutant Discharge Elimination System (NPDES) permits, or state or local water and air quality boards. The development of prepump separation modifications was motivated primarily by these discharge requirements, as the removal of LNAPL from the process stream prior to entering the liquid ring pump would reduce contaminant concentrations in both aqueous and vapor discharge streams.

The effectiveness of the two prepump separation methods was evaluated by comparing analytical results of the aqueous and vapor discharge samples collected before and after the incorporation of each of the prepump separation methods. Aqueous samples were analyzed for total petroleum hydrocarbons (TPH) and volatile organic compounds (VOCs) at a few sites. The volume of floating solids produced during the bioslurper operation was measured using graduated cylinders or drums. Qualitative judgments on the effectiveness of prepump separation were based on observations of the amount of floating solids present in the process water, and on the clarity of the aqueous discharge. Handheld TPH meters were used for routine field determinations of TPH concentrations in the vapor discharge. In addition, samples of the vapor discharge sample were collected using a Summa canister, and the TPH concentration was determined via laboratory analysis.

1.5 Previous Testing of the Technology

In the mid-1990s, systems were designed in an attempt to control the problems associated with the emulsions and floating solids produced during bioslurper activities. These systems included large-volume tanks for increased retention and separation time, tanks equipped with filter media to filter out the floating solids, and bag filters to strain the floating solids from the aqueous stream. In 1996 knockout tanks were designed by the U.S. Air Force and Battelle which would allow for prepump separation of the oil from the liquid stream. This knockout tank was equipped with level sensors and solenoid valves to "control" the liquid levels in the tank. However, the sensors and valves did not function quickly and the liquid levels could not be controlled.

In 1997, Battelle modified the knockout tanks by removing the level sensors and valves and designed the in-well oil/water separation system. The knockout tank system was tested at Naval Air Station (NAS) Fallon and Marine Corps Base Hawaii (MCBH) Kaneohe and used in full-scale operation at NAS Fallon, NAS Keflavik, and Marine Corps Base Hawaii (MCBH) Kaneohe. The short-term tests of the knockout tank indicated that the tank was effective at reducing the formation of floating solids, and decreased TPH concentrations in the bioslurper process water by 79%. The in-well separation system was tested short-term in a single well configuration at Coastal Systems Station (CSS) Panama City, MCBH Kaneohe, Naval Construction Battalion Center (NCBC) Davisville, and NAS Fallon. Tests of the dual drop tube demonstrated that the system decreased TPH concentrations in the process water by 88% on average. Short-term testing of both the knockout tank and in-well separation systems demonstrated that both systems would reduce the formation of the floating solids and minimize operation and maintenance efforts.

2.0 Technology Description

2.1 Background and Applications

2.1.1 Conventional Bioslurping Process

The bioslurping process combines vacuum-assisted LNAPL recovery with bioventing and SVE to simultaneously recover LNAPL and bioremediate the vadose zone. The process has been shown to improve LNAPL recovery efficiency compared to other recovery technologies (Battelle, 1997). The conventional system uses a single drop tube in each of the extraction wells to "slurp" LNAPL, groundwater, and soil gas. The system may pull a vacuum of up to 25 ft of water on the recovery wells in order to create the pressure gradient required to force movement of LNAPL into the wells. The system is operated to minimize drawdown of the water table, thus reducing the further creation of LNAPL smear zones.

Bioremediation of soils in the vadose zone is achieved by the extraction of soil gas; the extraction rate is controlled by the rate of LNAPL and groundwater recovery into the wells. The extraction of soil gas stimulates aerobic microbial activities in the vadose zone, thus enhancing the degradation of biodegradable hydrocarbons in contaminated areas. The SVE component of the bioslurping process becomes especially important when the removal of relatively volatile fuels (such as gasoline and jet propulsion [JP]-4) is the primary goal of the remedial action. When the LNAPL removal is complete, the bioslurper system can be easily converted to a conventional bioventing system for continuing remediation of the vadose zone soils.

Preliminary data from short-term pilot tests performed by Battelle for the Naval Facilities Engineering Service Center (NFESC) and the Air Force Center for Environmental Excellence (AFCEE) indicate that the LNAPL recovery rate achieved through bioslurping is up to six times greater than attainable through skimming and drawdown pumping. Mathematical modeling of drawdown pumping and bioslurping (Parker, 1996) predicts that bioslurping will remove free product three times faster than with drawdown pumping, while withdrawing seven times less groundwater.

A preliminary analysis of the available data indicates that bioslurping is a cost-effective technology for LNAPL recovery, with the benefit of simultaneous bioremediation of the vadose zone (Battelle, 1997). The process has been applied at sites with groundwater tables up to 210 ft below ground surface (bgs). Sites with deeper groundwater tables also may be managed after adjustments of some system components. A more detailed description of the bioslurping process can be found in *Principles and Practices of Bioslurping* (Place, et al., 2001).

2.1.2 Previous Emulsion Treatment/Control Attempts

Several techniques have been tested to treat and control the formation of emulsions and floating solids at a number of DoD sites. In early attempts, emulsions and floating solids were allowed to separate in several settling tanks that were added between the conventional OWS and the final discharge point (such as a sanitary sewer). This method, however, not only failed to remove the floating solids from the process stream, but also significantly increased waste handling problems because the floating solids and LNAPL were carried over from the OWS to all downstream settling tanks. Further, this technique had limited ability to separate the stable emulsions from the process stream.

Another attempt was made to address the floating solids problem by placing a “filtration tank” between the liquid ring pump and the OWS. The “filtration tank” consisted of a steel or polyethylene tank with two or three fibrous filters situated perpendicular to the direction of water flow. The “filtration tank” filled quickly with LNAPL and floating solids that not only rapidly clogged the filters but also moved downstream to the OWS and settling tanks. Therefore, extensive operation and maintenance (O&M) efforts would be required to maintain the system operation, and prolonged system downtime was experienced even during pilot-scale testing.

Attempts were made to effectively treat the stable oil/water emulsions in the process water exiting the OWS. One of the most promising methods was the use of a dissolved air flotation (DAF) system, which is widely available through various vendors. Before process water enters a DAF system, the water often needs to be treated with inorganic coagulants and/or polyelectrolytes at certain pH values. The microscopic bubbles produced in the DAF system will attach to the oil-laden flocs, causing them to float. The “float” is removed by a mechanical skimmer and transferred to a storage tank. The DAF-treated water is usually ready for discharge without further treatment. Although a DAF system was successfully implemented at one DoD site, it required more complex O&M and higher capital and O&M costs.

Because the postpump separation methods were not completely successful in capturing or controlling the emulsions and floating solids, attempts were made to prevent the formation of emulsions and solids using prepump knockout tanks (i.e., OWSs under vacuum). The knockout tanks were designed to separate extracted LNAPL from the process water before it reached the liquid ring pump. This method involved the use of a vacuum/pressure cylinder assembly placed between the bioslurper well manifold and the liquid ring pump. Field tests of this method enjoyed only limited success because the design of the tanks did not allow for satisfactory oil/water separation and because of the necessary maintenance of a constant water/LNAPL level in the tanks.

2.1.3 Prepump Separation (Technologies used during the Demonstrations)

Prepump separation of LNAPL prevents the formation of emulsions and floating solids in the bioslurper process effluent, thus minimizing/eliminating the need for downstream water treatment before disposal. An additional benefit of the prepump separation is the decreased contaminant concentrations in the process off-gas discharge.

Several prepump separation methods have been developed and demonstrated by Battelle, the Navy, and ESTCP. The most promising methods include the use of dual drop tubes for in-well separation of LNAPL from water and soil gas (i.e., extracting LNAPL and water/soil gas in two separate streams), and the use of a prepump knockout tank to separate LNAPL from the liquid stream prior to the entry of the stream into the liquid ring pump.

The knockout tanks have been modified to eliminate an initially devised level-control device (common to most commercial knockout tank designs), thus simplifying the operation of the tanks. This modification improved the separation capability of the tanks and significantly minimized the O&M requirements. The extracted LNAPL, groundwater, and soil gas from the extraction manifold enter the tank through a tee located above the LNAPL level in the tank (Figure 2-1). The top section of the tee allows soil gas to vent into the top one-third portion of

the tank. The bottom section of the tee extends about 0.5 to 1 ft below the water level and allows LNAPL and groundwater to drain into the bottom two-thirds portion of the tank. The liquid level is maintained by the location of a tee fitting on the effluent side of the tank. Soil gas exits the tank via an exit pipe located near the top of the tank. Groundwater exits through a similar exit pipe located near the bottom of the tank. The soil-gas and groundwater streams meet at the tee fitting before being vacuumed into the liquid ring pump. The LNAPL that accumulates in the tank overflows an exit weir into a fuel storage tank that also is maintained under vacuum. The LNAPL may be manually drained (if the LNAPL-recovery rate is relatively low) from the fuel storage tank and transferred to a large LNAPL storage tank. Field demonstrations indicate that the use of a knockout tank can control the formation of emulsions and floating solids and decrease TPH concentrations in the liquid ring pump stack gas and effluent water. Figure 2-2 shows a knockout tank on a mobile bioslurper system that was used during the demonstration.

The use of a dual drop tube configuration placed in front of the liquid ring pump also significantly reduces the formation of stable emulsions and floating solids. This method prevents mixing of LNAPL and groundwater during the slurping action in the extraction manifold, thereby minimizing/eliminating the formation potential. Similar to the conventional single drop tube configuration, the pressure gradient induced by the vacuum draws LNAPL, groundwater, and soil gas to the extraction wells. However, LNAPL is removed from the wells via one drop tube while groundwater and soil gas are removed via the other (Figure 2-3). The drop tube that extracts groundwater and soil gas is guarded by a shield. This arrangement allows groundwater to be drawn through the bottom of the shield and soil gas through the top. The drop tube that extracts LNAPL is located outside the shield, with the opening of the tube generally placed approximately 0.25 inch above the oil/water interface. The recovered groundwater and soil gas enter the liquid ring pump. The groundwater then exits the pump to the OWS, and the soil gas exits the pump out of a stack. The recovered LNAPL, drawn to the surface by the bioslurper vacuum pump, is captured in a separate tank (under vacuum) for temporary storage. Because the mixing between LNAPL and groundwater is minimized in the extraction manifold, downstream treatment of groundwater may not be required before final discharge. Figure 2-4 shows a photograph of the dual drop tube system.

2.2 Advantages and Limitations of the Technology

2.2.1 Conventional Bioslurping Process

The major advantage of the bioslurping process is that the technology provides LNAPL recovery while simultaneously remediating vadose zone soils through bioventing and SVE. Bioslurping has been demonstrated to exceed skimming and pump drawdown as an LNAPL-recovery technology. It is applicable to many LNAPL-contaminated sites, and can be converted easily to a bioventing system when LNAPL recovery is complete. The major limitations of the process include reduced effectiveness in low-permeability soils and the tendency to form stable oil/water emulsions and floating solids in the aqueous discharge from the liquid ring vacuum pump. The process also increases TPH concentrations in the stack gas. The presence of emulsions and floating solids often impedes the effectiveness of the OWS and requires complex and expensive water treatment processes before the process water can be discharged. The TPH-rich stack gas also may need treatment before its final discharge.

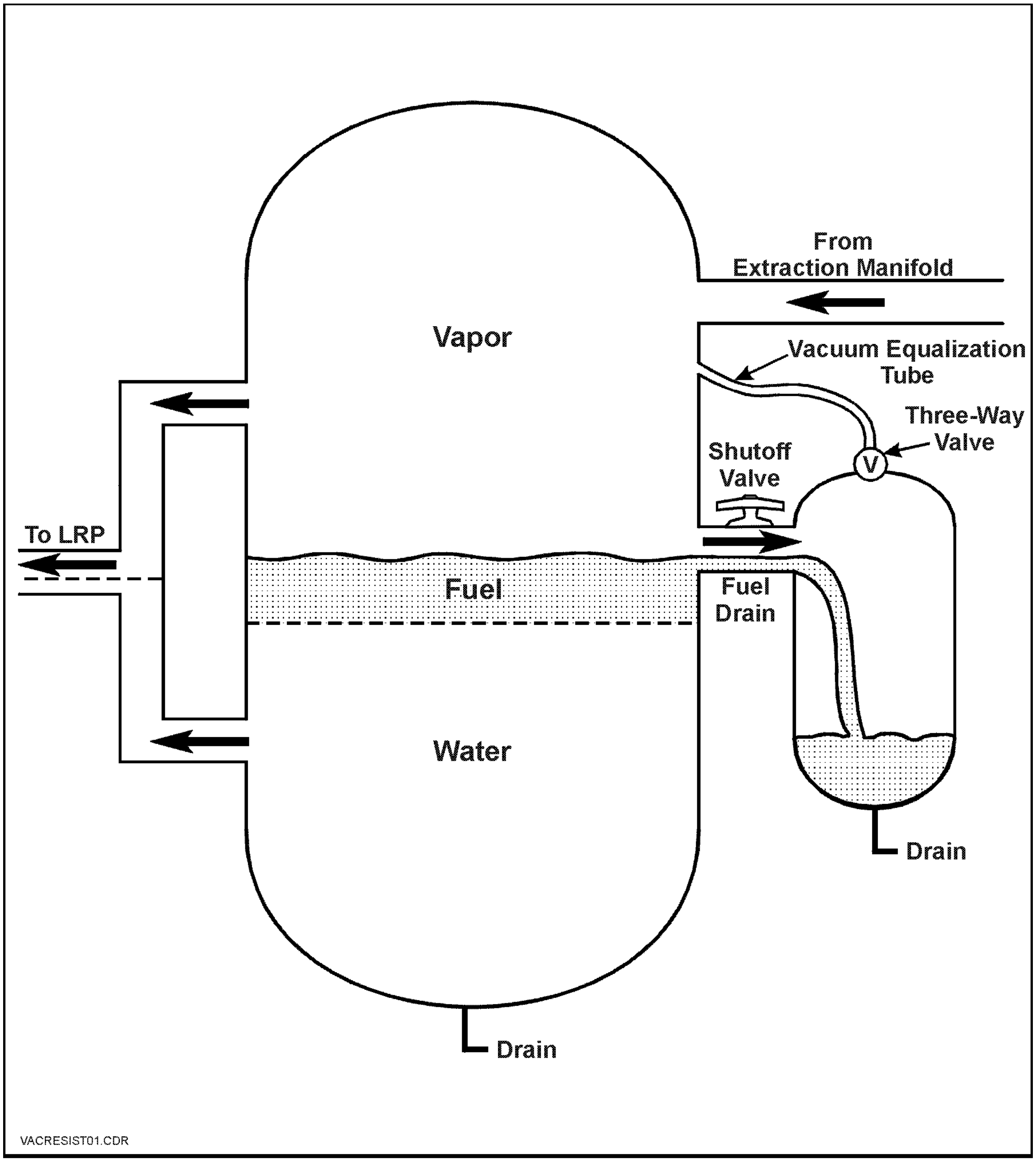

Figure 2-1. Vacuum-Resistant Separator

Figure 2-2. Vacuum-Resistant Separator on Mobile Bioslurper System

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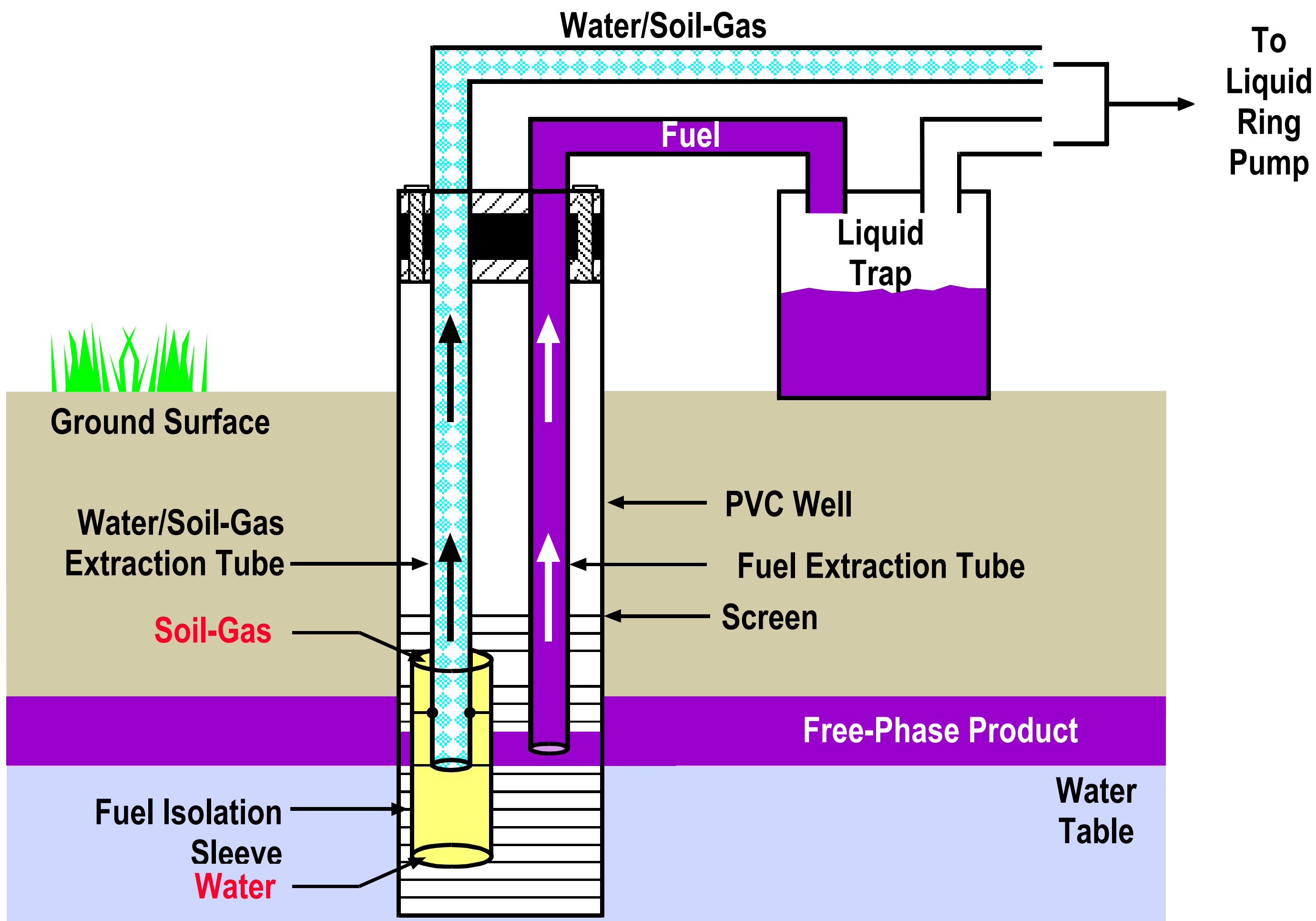

Figure 2-3. Schematic of Dual Drop Tube

Figure 2-4. Photograph of the In-Well Pieces Dual Drop tube System Displaying the Soil Gas/Groundwater Drop tube, the Field Shield and The Fuel Extraction Drop Tube

2.2.2 Prepump Separation

Reduced petroleum hydrocarbon concentrations in the discharge streams from the bioslurper and reduced formation potential of stable emulsions and floating solids in the process water are the primary advantages of the prepump separation modifications. Prepump separation will remove recovered LNAPL from the liquid stream prior to the entry of the stream into the liquid ring pump, thus preventing the turbulent mixing of LNAPL and process water within the pump head. These advantages will make the bioslurping process a more attractive option for implementation because of reduced needs for downstream water and stack gas treatment. When the dual drop tube system is being operated in a multiple-well configuration, the depth of the drop tubes may need to be monitored and adjusted on a routine basis to achieve proper flow of the fluids out of the well and optimum performance of the system. If drop tubes are not properly set, the dual drop system will not perform to its potential, and the petroleum hydrocarbon concentrations in the discharge streams will be more similar to those during operation in the standard bioslurper configuration. The effects of water table fluctuation on the placement of drop tubes are not completely clear either, especially when a large number of extraction wells are joined by a manifold during the full-scale implementation. Based on observations at previous prepump separator demonstrations, however, fluctuations in the water table have had little effect on these operating parameters.

3.0 Site Descriptions

3.1 Background

Several selection criteria were considered during the site selection for these technology demonstrations. The overriding requirement was the presence of LNAPL contamination at candidate sites. For the selection of the long-term site, the site needed to contain sufficient LNAPL to sustain recovery for four months of bioslurper operation. Also, conditions at these sites were selected to allow the use of the bioslurper system to recover LNAPL (i.e., soils must be sufficiently permeable to permit LNAPL flow while still being “tight” enough to allow the bioslurper system to create a vacuum-induced pressure gradient). Eight sites were selected for the short-term demonstrations, and one of the short-term sites (NAS Fallon) was selected for the long-term demonstration. NAS Fallon was selected because it was the most likely site to produce LNAPL over the four-month demonstration and the plume was large enough to install several wells. All of the sites except for Tyndall AFB were using or had planned to use an LNAPL-extraction system. In most cases, a conventional bioslurper system was to be used at the site.

To demonstrate the effectiveness of the prepump separation improvements to the bioslurper system, the following factors also were considered:

- Presence of LNAPL and depth to groundwater
- Type of LNAPL contamination (e.g., gasoline, diesel, jet fuel, etc.)
- Soil conditions
- Tendency of LNAPL at the site to form stable emulsions and floating solids during extraction
- Logistic considerations (e.g., power availability, aqueous discharge facilities, regulatory requirements, Base support, etc.).

Table 3-1 and Figure 3-1 summarize the relevant information about these sites.

Table 3-1. Summary of Selection Criteria Information at the Demonstration Sites

Site Location	Type of LNAPL	Thickness of LNAPL (ft)	Depth to Groundwater (ft)	Recovery Rate of LNAPL	Formation of Emulsions
NCBC Davisville, RI	No. 2 Fuel Oil	1.0	5-15	Low	Moderate
NAS Fallon, NV	JP-5	0-2.5	7-11	High	Moderate
NAWC China Lake, CA	JP-5	1.0-3.5	45-50	Moderate	Moderate
Bolling AFB, DC	No. 2 Fuel Oil	0-3.0	5-10	Low	High
Tyndall AFB, FL	JP-4	0-2.0	7-13	Low	Moderate
NFD Point Molate, CA	Bunker and JP-5	0.5	10-15	Low	High
MCAS Cherry Point, NC	No. 2 Fuel Oil	0.2 – 2.0	5-8	Low	Moderate
Hickam AFB, HI	JP-4	0.5-3.0	11-14	Low	Moderate

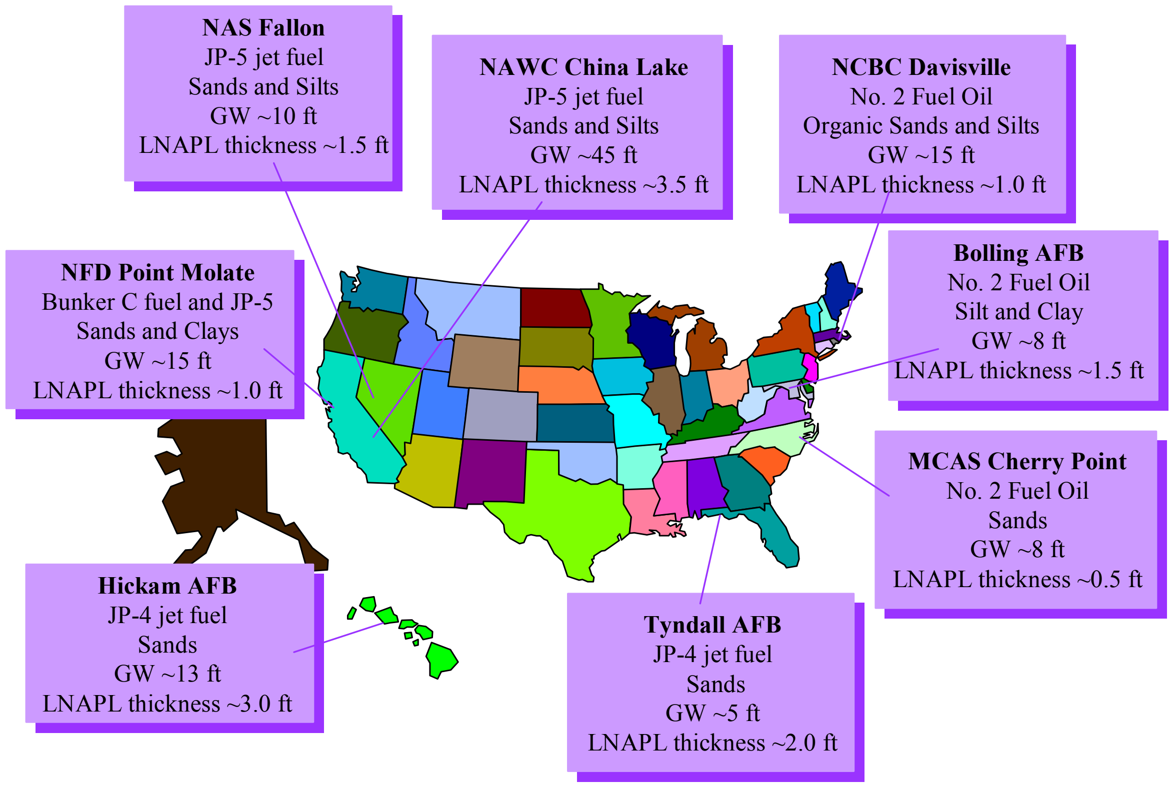

Figure 3-1. Demonstration Site Information

3.1.1 Naval Construction Battalion Center (NCBC), Davisville, Rhode Island

Battelle conducted a bioslurper pilot-scale study at Environmental Baseline Survey (EBS) Site 21 at NCBC in Davisville, Rhode Island, in 1998 (Battelle, 1999). In addition, site characterization was performed using a Site Characterization and Analysis Penetrometer System (SCAPS) investigation in 1998. Data collected during the pilot-scale testing were used to determine if this site would be applicable as an ESTCP short-term demonstration site.

3.1.1.1 Site Location and History

NCBC Davisville is located on 1,284 acres in the northeast section of North Kingstown, Rhode Island, 15 miles southeast of the city of Providence. The Base residential areas lie to the north, commercial development lies to the west, the decommissioned NAS Quonset Point lies to the south, and Narragansett Bay lies to the east. EBS Site 21 is the former location of Tank DC-133. Tank DC-133 was a 42,000-gallon-capacity steel storage tank, which contained No. 2 fuel oil. EBS Site 21 is displayed in Figure 3-2.

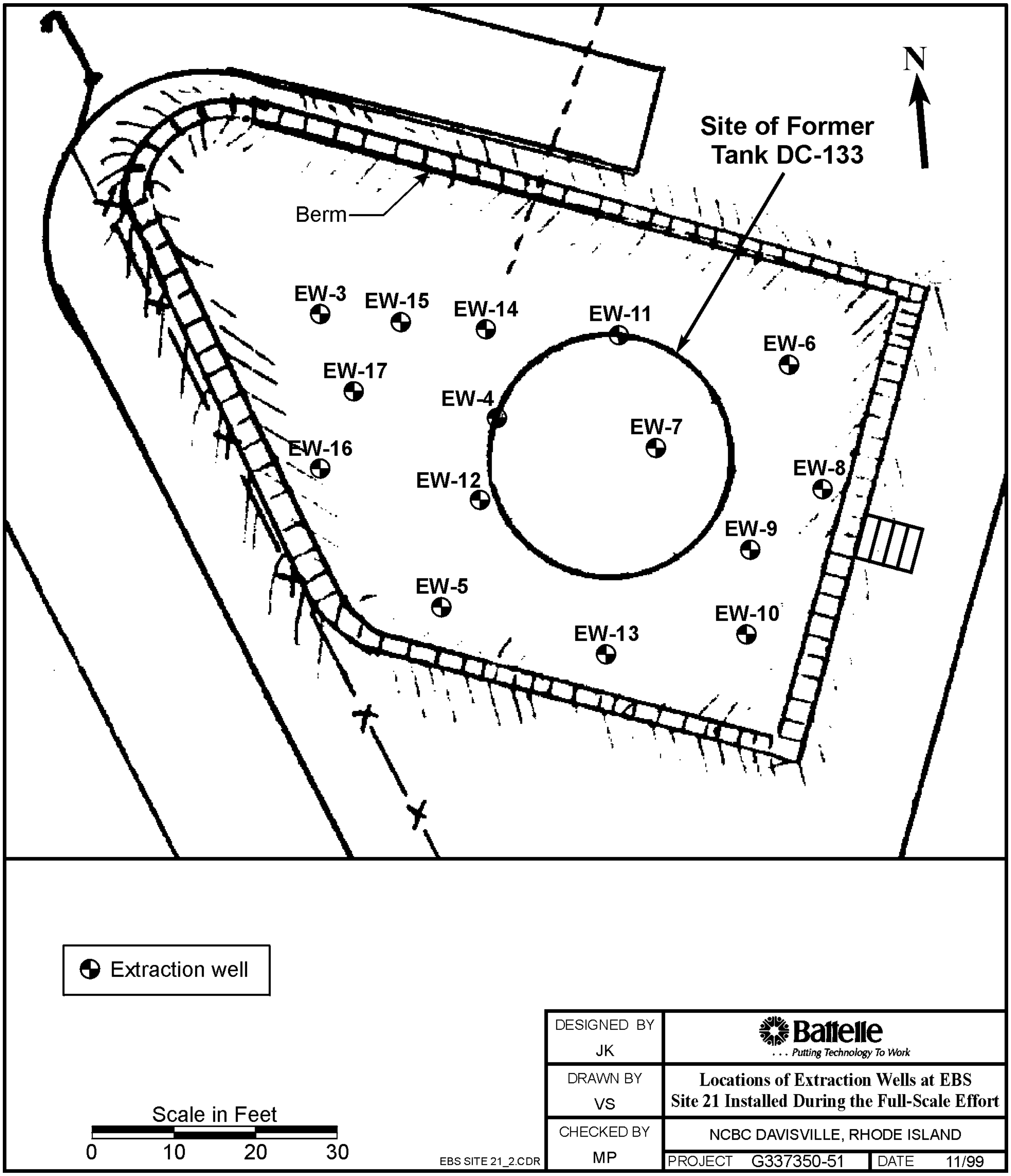

Figure 3-2. NCBC Davisville, RI, EBS Site 21 Map

3.1.1.2 Presence of LNAPL and Depth to Groundwater

During baildown testing, LNAPL was detected at an initial thickness of 0.69 ft in one (EW-3) of the five extraction wells installed by Battelle. Two baildown tests, one lasting about 13 hours and the other about 8 hours, were conducted at EW-3 to provide a qualitative indication of the presence of LNAPL and of the recovery potential. The second baildown test was conducted to determine if LNAPL recovery was originating from the sand pack around the well. About 40 gallons of LNAPL was recovered during the original bioslurper pilot-scale testing.

3.1.1.3 Type of LNAPL

The fuel contamination at EBS Site 21 likely originated from the 42,000-gal steel storage tank used to contain No. 2 fuel oil.

3.1.1.4 Soil Conditions

Site lithology was characterized by observation of drill cuttings during the extraction well installation. The majority of the vadose soils are moderate to coarse sand with some pebble-size gravel. Below the water table the soil consists of fine sands and silts with lenses of peat. This soil composition was acceptable for LNAPL flow, but the soils contained enough organic matter to minimize LNAPL flowrates.

3.1.1.5 Tendency of LNAPL to Form Emulsions

During the pilot-scale study, stable oil/water emulsions and floating solids were formed. The floating solids were stable and dark in color. The emulsions caused the process water to appear milky white. The TPH concentrations of the process water ranged between 265 and 560 mg/L at extraction well EW-3.

3.1.1.6 Logistic Considerations

All logistic considerations were addressed for the short-term demonstration. A generator was required to supply the electrical power for the bioslurper. The allowable TPH discharge limit of 1 mg/L for wastewater, set by the Rhode Island Department of Environmental Management, was exceeded in some cases during the pilot-scale testing performed in 1998. Therefore, further treatment of the process water was required before disposal during the ESTCP short-term demonstration. There were no applicable vapor discharge limits because of the short time period of the pilot-scale testing and the expected low vapor release rate. During the pilot-scale testing, hydrocarbon removal rates were estimated at approximately 5.75 and 0.005 lb/day of TPH and benzene, respectively.

3.1.2 Naval Air Station (NAS), Fallon, Nevada

Bioslurping activities have been conducted at NAS Fallon Site 2. Information concerning site conditions and background was obtained from a remedial investigation (RI) conducted by Oak Ridge National Laboratory (ORNL) in 1994 (ORNL, 1994).

3.1.2.1 Site Location and History

NAS Fallon is located in Nevada, 6 miles southeast of the town of Fallon and 60 miles east of Reno. NAS Fallon was established originally as a military facility in 1942 as part of the Western Defense Program (ORNL, 1991). The Base was commissioned as a Naval Air Auxiliary Station

(NAAS) in 1944, and went through varying degrees of activity through the 1950s and 1960s before being upgraded to Naval Air Station in 1972 (ORNL, 1991). NAS Fallon serves as an aircraft weapons delivery and tactical air combat training facility.

The New Fuel Farm (Site 2) is located in the northwestern portion of NAS Fallon, as shown in Figure 3-3. Approximately 3,300,500 gallons of JP-8 jet fuel reside in three underground and three aboveground storage tanks located at Site 2. However, until a few years ago, the primary fuel at the fuel farm was JP-5 jet fuel. Most of the contamination around the fuel farm appears to be JP-5 with minor amounts of gasoline. The New Fuel Farm at Site 2 reportedly was constructed in 1957 to provide fuel delivery services for NAS Fallon. Stored fuels include jet fuel, aviation gasoline, diesel, and motor gasoline.

3.1.2.2 Presence of LNAPL and Depth to Groundwater

Historically, LNAPL has been detected floating on top of the shallow groundwater table. This LNAPL thickness has ranged approximately between 0 and 2.5 ft. Active LNAPL removal is taking place by bioslurping and pumping free product from the groundwater surface using a peristaltic pump.

The local groundwater table is situated at depths ranging from 7 to 11 ft bgs.

3.1.2.3 Type of LNAPL

The existing fuel contamination at the site is composed mostly of JP-5, but some aviation gasoline and motor vehicle gasoline have been stored at the New Fuel Farm in the past.

3.1.2.4 Soil Conditions

The vadose zone is composed primarily of soils classified as clay loam. The local water table is situated at depths ranging from 7 to 11 ft bgs, and is located at the top of a 3-ft-thick fine sand layer that overlies a thick regional lacustrine clay stratum. This soil composition allowed for LNAPL flow, yet was "tight" enough to create a vacuum-induced pressure gradient.

3.1.2.5 Tendency of LNAPL to Form Emulsions

Light to moderate emulsions were observed during past bioslurping activities at Site 2.

3.1.2.6 Logistical Considerations

Power is available near the site, but some coordination was required to use it for bioslurping activities. Process water was limited to a discharge rate of 5 gallons per minute (gpm) for direct disposal to the Base sanitary sewer system. No vapor discharge permit was required because emissions were expected to be much less than the 4,000-lb-per-year regulatory action threshold for volatile organic compounds (VOCs) emitted from petroleum-contaminated soil or a groundwater treatment system.

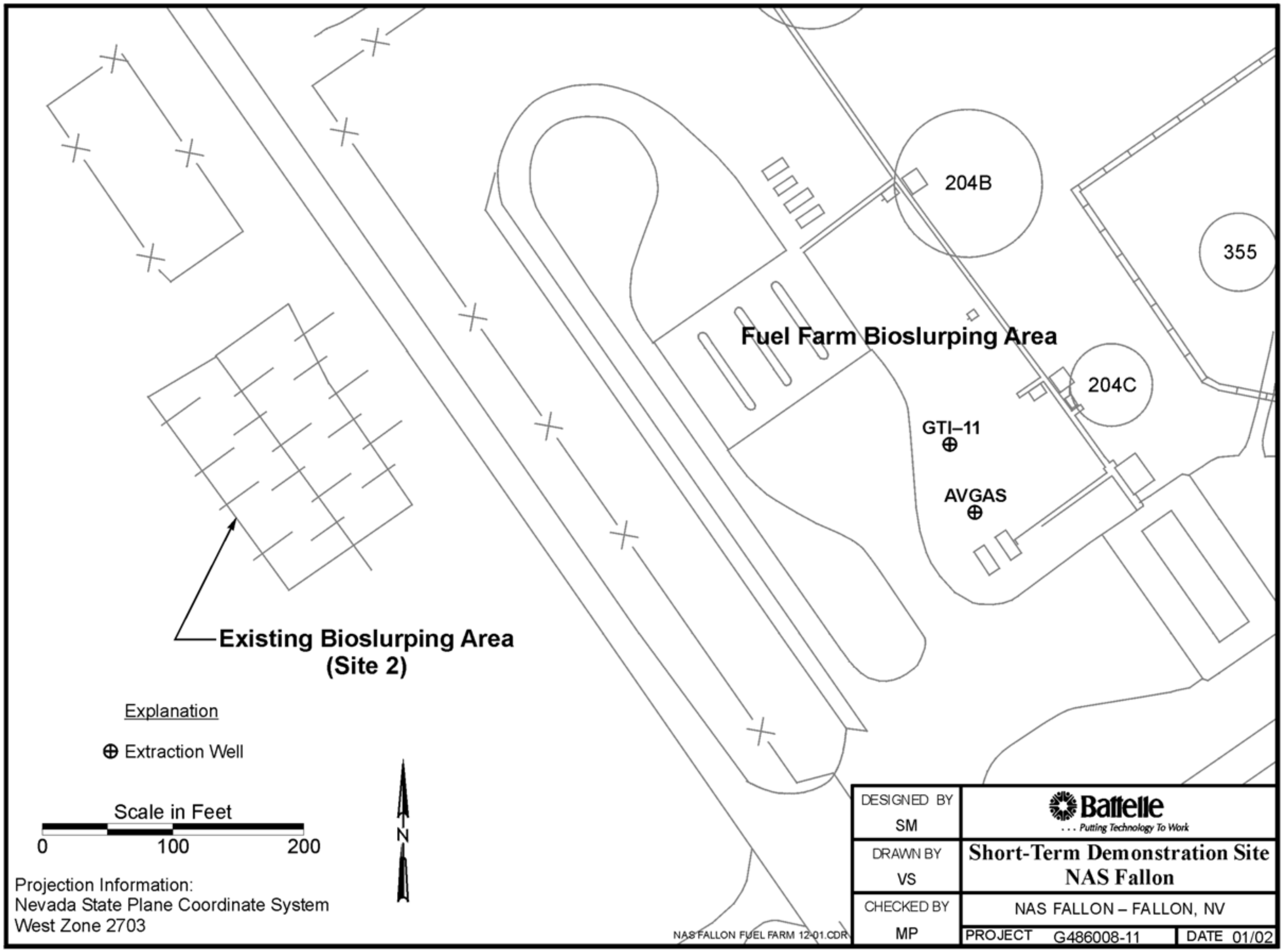

Figure 3-3. New Fuel Farm (Site 2) is Located in the Northwestern Portion of NAS Fallon

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3.1.3 Naval Air Weapons Center (NAWC) China Lake, California

NAWC China Lake is located just to the north of the town of Ridgecrest, California, approximately 120 miles northeast of Los Angeles. The facility encompasses over 1.1 million acres of land. NAWC was established in 1943 to provide research, development, testing and evaluation of weapons systems for the Navy. The facility has continued to function as a development facility to the present.

NAWC China Lake is located in the upper Mojave Desert approximately 150 miles northeast of Los Angeles. The installation encompasses about 1.1 million acres and is comprised of two separate areas: the China Lake Complex (North Range) and the Randsburg Wash/Mojave B complex (South Range). The Armitage Field Former Fuel Farm is located in the China Lake Complex, which lies in portions of Kern, Inyo, and San Bernadino Counties.

The Armitage Field Former Fuel Farm is located approximately 3 miles north of the town of Ridgecrest in the southern portion of NAWC China Lake. The former fuel farm is approximately 450 x 400 ft and is bordered by parking to the north, undeveloped desert to the south and east, and Base facilities to the west. There were six underground storage tanks when the fuel farm was operating.

3.1.3.1 Site Location and History

NAWC China Lake and Armitage Field were constructed in 1943 (Figure 3-4). Armitage Field was established in 1945 with two 100,000-gallon and four 50,000-gallon underground storage tanks. In addition, one 40,000-gallon tank was installed for waste oil. Several different types of fuel were stored in the tanks over the years including: JP-3, JP-4, JP-5, avgas 115/145, and avgas 100/130.

3.1.3.2 Presence of LNAPL and Depth to Groundwater

This LNAPL thickness has ranged between approximately 1.0 and 3.5 ft. As was the practice of the day, off-specification fuel was drained to dry sumps or directly to the ground. Estimates of the volume of LNAPL present at the site range from 20,000 to 70,000 gallons.

The local groundwater table is situated at depths ranging from 45 to 50 ft bgs. The general groundwater flow direction is northeast toward the China Lake Playa.

3.1.3.3 Type of LNAPL

The existing fuel contamination at the site is composed mostly of JP-5. However, due to the fact that many different types of fuel have been stored at the facility over time, other types of fuel likely are present in the subsurface.

3.1.3.4 Soil Conditions

Armitage Field primarily consists of quaternary alluvial, and to a lesser extent, lacustrine deposits. A discontinuous layer of interfingering gray, sandy, plastic clay is present at about 25 to 40 ft bgs. A sandy silt to well-graded sand is present to approximately 25 ft bgs; however,

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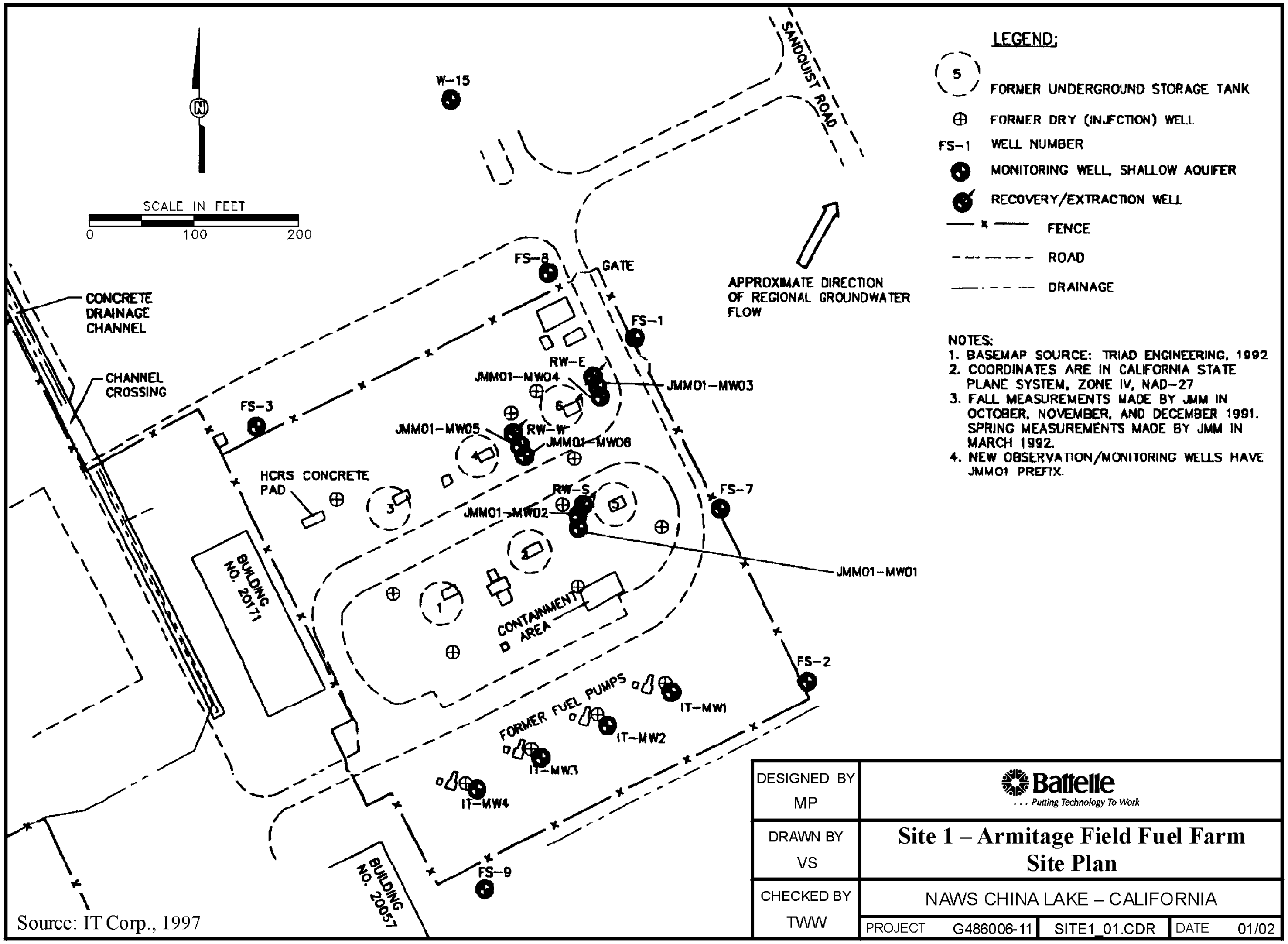

Figure 3-4. Site 1 Armitage Field Fuel Farm Site Plan, NAWS China Lake

caliche is present throughout this layer. Sands and silty sands interbedded with silt and clay layers are present to a depth of 90 ft bgs, where they are underlain by clay-rich lacustrine deposits.

3.1.3.5 Tendency of LNAPL to Form Emulsions

A short-term LNAPL removal test was conducted at the facility in 1998, but the emulsions were not quantified or qualified.

3.1.3.6 Logistical Considerations

A generator was required to supply the electrical power for the bioslurper. The water was treated by clay and carbon drums and then discharged into the sewer system. There were no applicable vapor discharge limits because of the short time period of the pilot-scale testing and the expected low vapor release rate.

3.1.4 Bolling Air Force Base (AFB), Washington, DC

Bolling AFB is located along the Potomac River in Washington, DC. Bolling AFB provides logistical support for the national capital and provides administrative support for the Air Force.

3.1.4.1 Site Location and History

Site SS-03 is associated with the Heat Plant, Building 18 (Figure 3-5). The Heat Plant utilized six underground heating oil storage tanks. Two of the tanks were twin 75,000-gallon concrete chambers within a single concrete vault which was divided by a concrete wall. These tanks were installed in 1972 and were taken out of service in 1991 after failing tightness tests. Another large capacity (120,000 gallon) concrete tank was abandoned to accommodate heat plant expansion. The tank was reportedly abandoned by removing the concrete top and puncturing the floor, allowing an unknown quantity of remaining oil to drain out. Various oil spills have reportedly occurred in the past in the vicinity of the tanks. A large spill occurred when an underground pipe was left uncapped after the fourth 25,000-gallon steel tank was removed. Another large spill occurred when underground lines from the reserve 25,000-gallon tanks ruptured. The dates and quantities of these spills have not been identified.

During the months of August and September 1998, a bioslurper remediation system at Site SS-03 was expanded to include five new bioslurper wells in addition to the two existing bioslurper wells presently being used to recover product. Figure 3-5 presents the new well locations and the orientation of the trenching network.

3.1.4.2 Presence of LNAPL and Depth to Groundwater

Originally, LNAPL was detected in the electrical utility vault near the storage tanks. After the LNAPL was detected in the utility vault, monitoring and extraction wells were installed. Routinely, LNAPL has been detected in the site wells ranging from nondetectable levels to approximately 3 ft thick. A bioslurper system was installed in 1995 to remove the recoverable LNAPL from the site.

The local groundwater table is situated at depths ranging from 5 to 10 ft bgs.

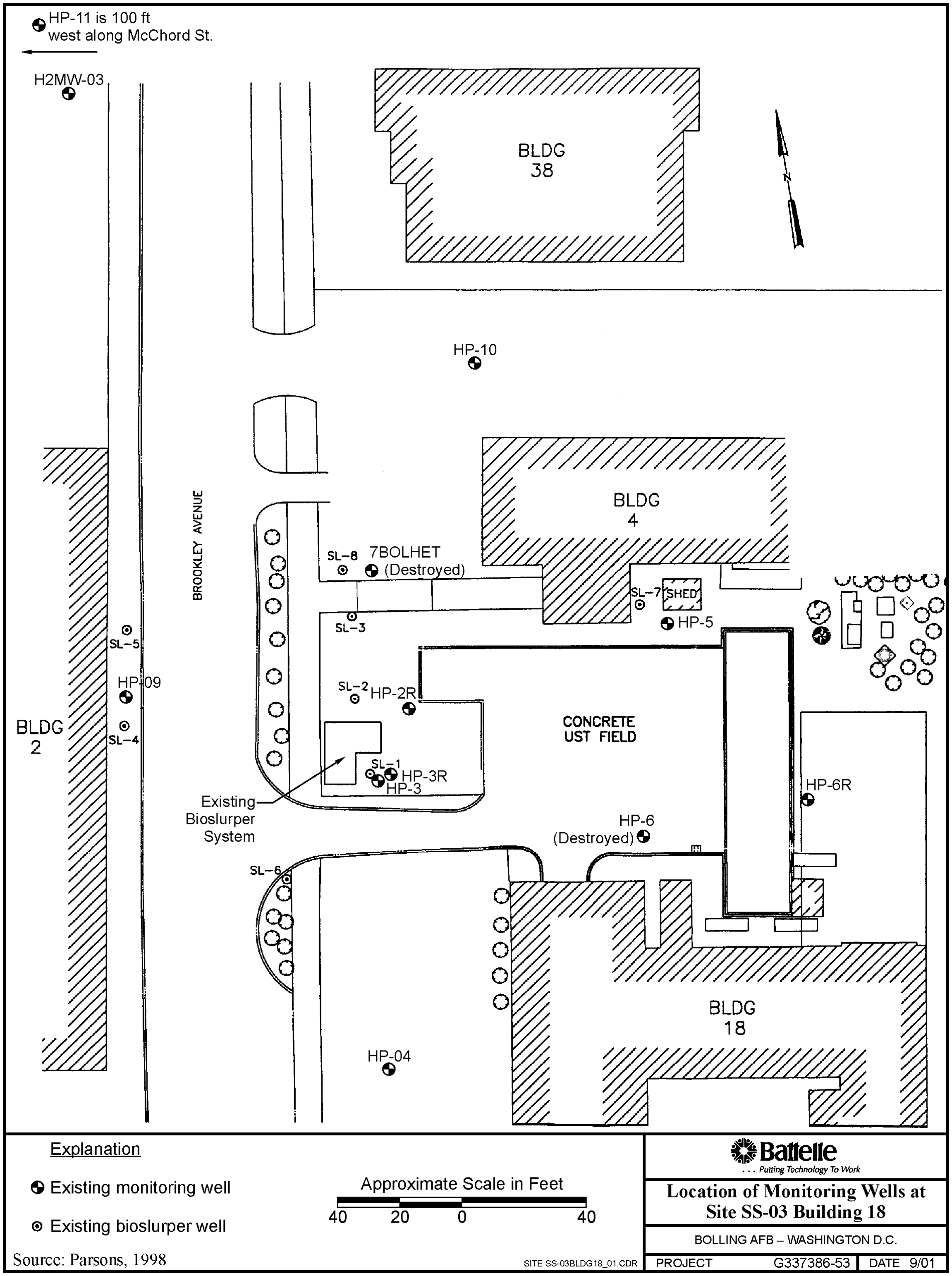

Figure 3-5. Location of Monitoring Wells at Site SS-03 Building 18

3.1.4.3 Type of LNAPL

The existing LNAPL at the site is composed of No. 2 heating oil, which originated from leaking storage tanks near the heating plant.

3.1.4.4 Soil Conditions

The vadose zone is composed primarily of sandy or silty soils. Below the water table, the grain-size distribution of the soil increases; the soils are primarily coarse sands and fine gravels. The fine-grained soils near the surface allowed the vacuum generated by the bioslurper system to be contained in the subsurface.

3.1.4.5 Tendency of LNAPL to Form Emulsions

Heavy emulsions were observed during past bioslurping activities at the heating plant site.

3.1.4.6 Logistical Considerations

Initially, an electrical generator was required to power the bioslurper pump. However, after a few days of operation, satisfactory electrical service was located for the pump, and the system was switched to line power. The water was discharged to the sanitary power system after passing through a base-owned water treatment system.

3.1.5 Tyndall Air Force Base (AFB), Tyndall, Florida

Tyndall AFB is located in an area of the Florida panhandle and is part of the eastern Gulf of Mexico sedimentary basin. Tyndall is approximately 12 miles east of Panama City.

3.1.5.1 Site Location and History

The system was located at a former petroleum, oils, and lubricant (POL) site at Tyndall AFB, Florida. The site served as a fuel supply area from 1943 through 1987 (CH_2M Hill, 1981). The site contained 17 tanks with a combined capacity of 491,000 gallons. JP-4 jet fuel, #2 diesel fuel, and MOGAS (motor fuel) were stored in these tanks (Figure 3-6). Several of the tanks developed leaks resulting in soil and groundwater contamination at the site.

3.1.5.2 Presence of LNAPL and Depth to Groundwater

LNAPL has been detected in the site wells ranging from nondetectable levels to approximately 2 ft thick.

The average depth to groundwater varies from about 1 to 10 ft over most of the Base, but may be as deep as 15 ft in some areas. The site's average groundwater level was between 7 and 13 ft bgs.

3.1.5.3 Type of LNAPL

The fuel contamination at POL-B likely originated from one of the fuel storage tanks used to contain JP-4.

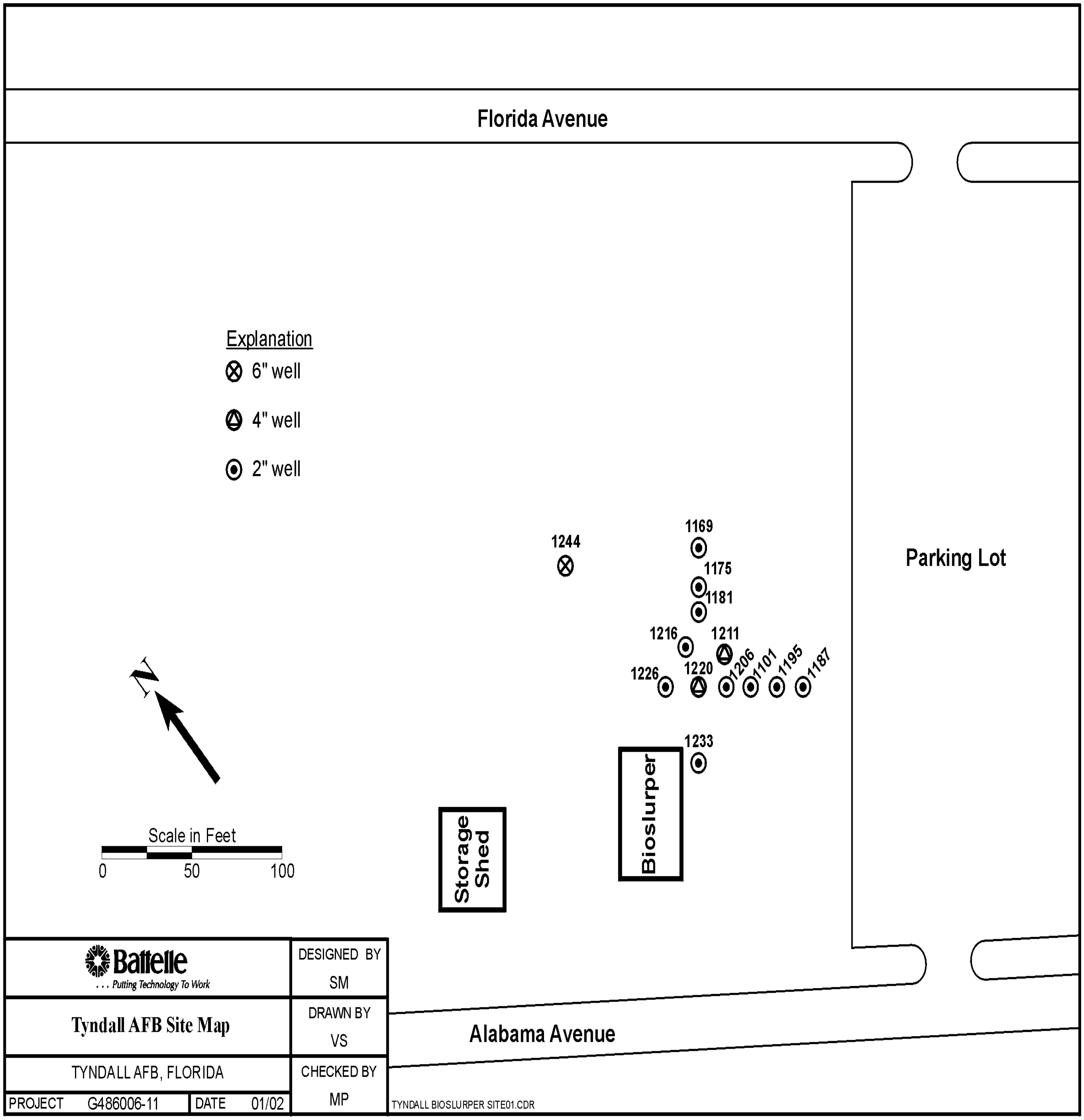

Figure 3-6. Tyndall AFB POL B Site Map

3.1.5.4 Soil Conditions

The uppermost sediments of the region are made of sands and gravel which are approximately 100 ft thick. These sediments are moderately permeable and transmit water readily. However,

occasional clayey sand and hardpan layers occur at varying depths within the formation resulting in the impediment of downward groundwater movement.

3.1.5.5 Tendency of LNAPL to Form Emulsions

Moderate emulsions were observed during past bioslurping activities at Tyndall AFB.

3.1.5.6 Logistical Considerations

Power is available near the site, but some coordination was required to use it for bioslurping activities. Process water was limited to a discharge rate of 5 gpm for direct disposal to the Base sanitary sewer system. No vapor discharge permit was required because emissions were expected to be less than regulatory action threshold for VOCs emitted from petroleum-contaminated soil or a groundwater treatment system.

3.1.6 Naval Fuel Depot (NFD) Point Molate, California

The Base is located in Contra Costa County in the city of Richmond. It is bordered by the San Francisco Bay and Chevron oil refinery. It is in proximity to the Richmond-San Rafael Bridge.

3.1.6.1 Site Location and History

The system is located near the center of the former fuel storage tanks and fuel distribution systems. The tanks were used for storage of fuels and oils, and the LNAPL contamination likely occurred over a period of years from leaking distribution lines (Figures 3-7 and 3-8).

3.1.6.2 Presence of LNAPL and Depth to Groundwater

LNAPL has been detected in the site wells ranging from nondetectable levels to approximately 0.5 ft thick.

The site has an average groundwater level between 10 and 15 ft bgs.

3.1.6.3 Type of LNAPL

The fuel contamination at the site is JP-5 and Bunker C.

3.1.6.4 Soil Conditions

The near-surface soils at NFD Point Molate are composed mostly of fill materials and the physical properties of the soil are extremely variable across the site. The wells that were used displayed acceptable vacuum levels during the demonstration.

3.1.6.5 Tendency of LNAPL to Form Emulsions

Bioslurping or vacuum-enhanced recovery had not been performed at this site, so emulsion formation data are not available. However, prior to the short-term demonstration, it was believed that significant emulsions and floating solids would be formed because of the viscosity of the product.

3.1.6.6 Logistical Considerations

The electrical power required to operate the bioslurper system was not available across the entire base; therefore, a generator was used to allow the bioslurper to be moved to different wells.

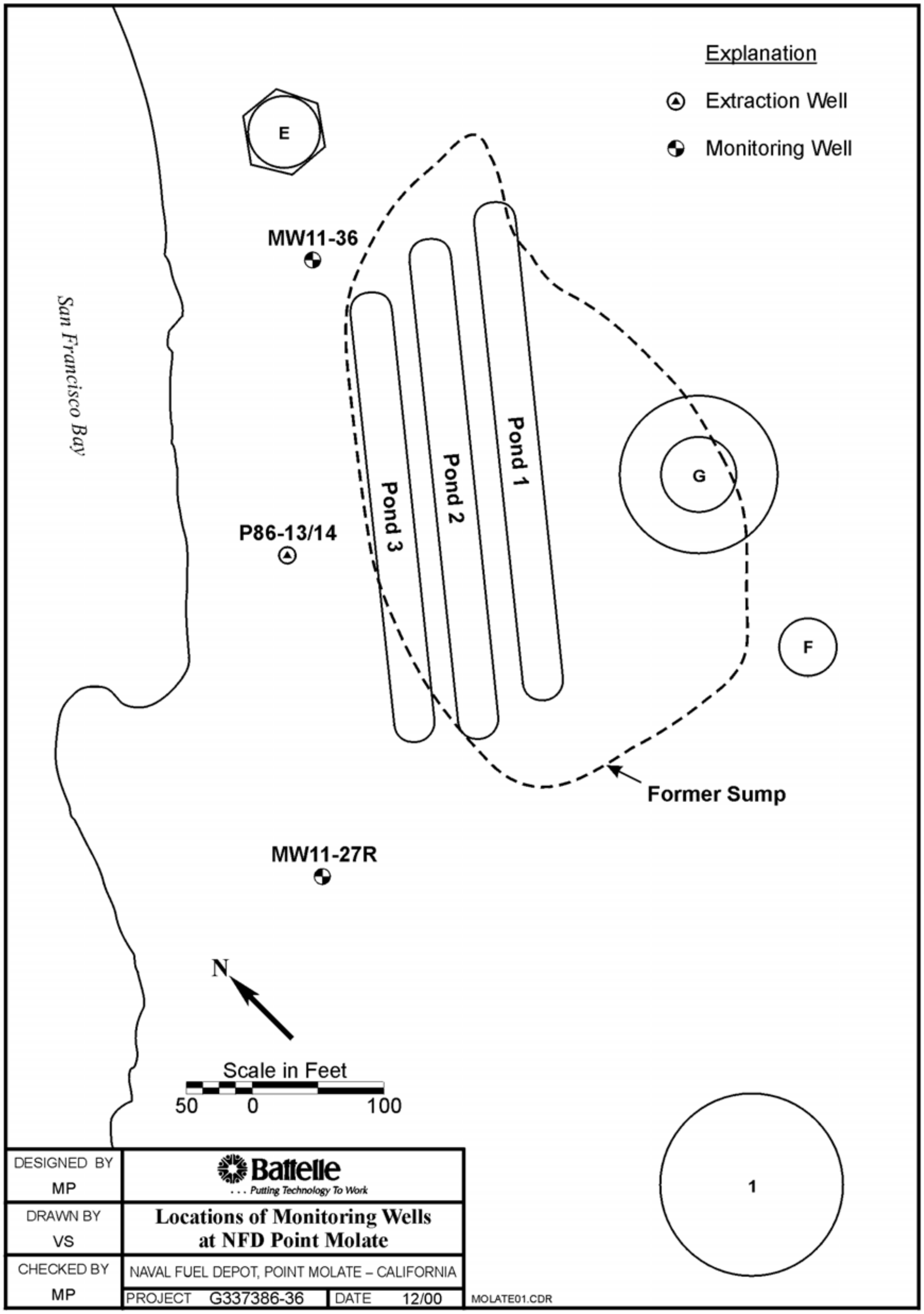

Figure 3-7. Locations of Monitoring Wells at NFD Point Molate Used During the In-Well Separation Demonstration

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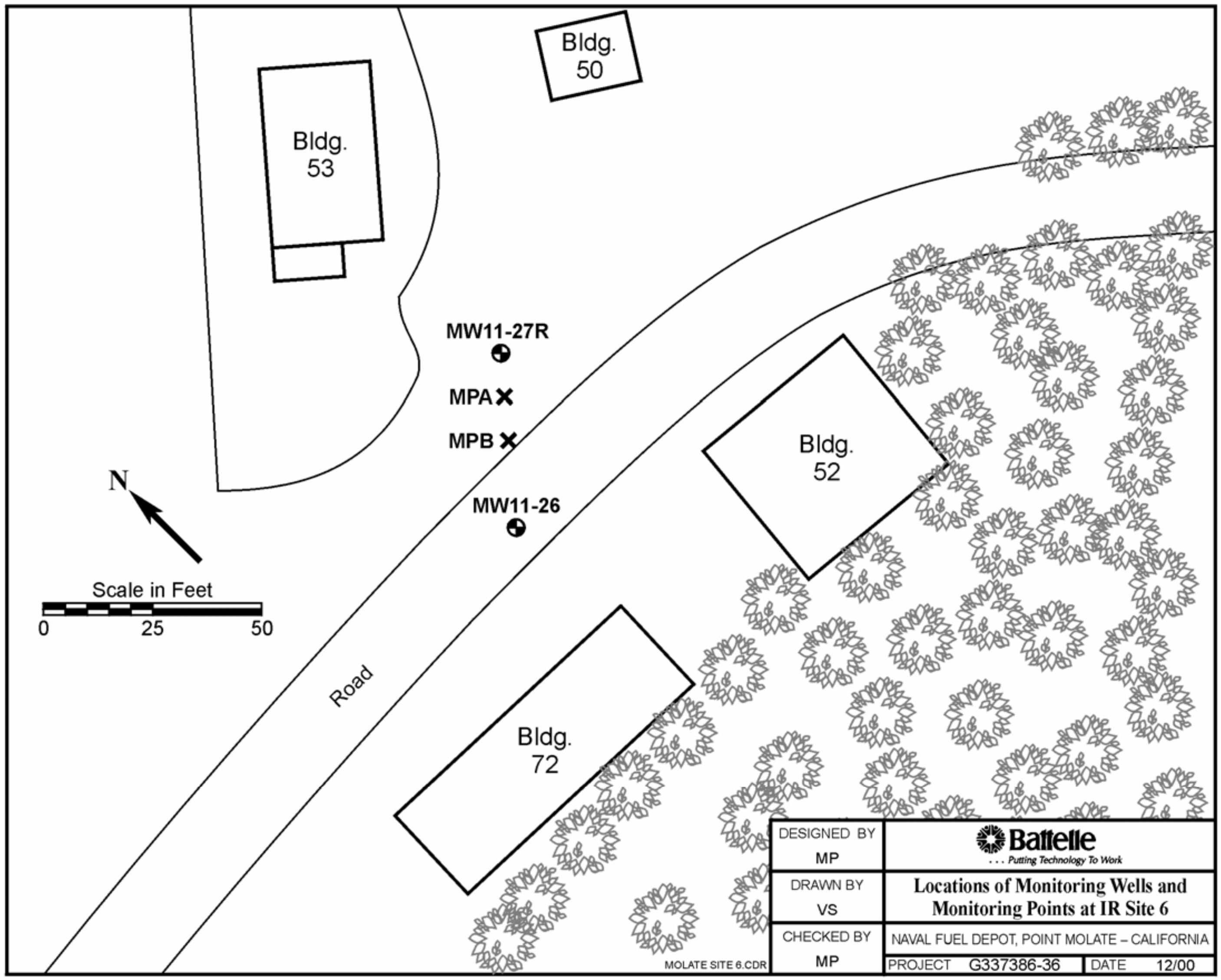


Figure 3-8. Location of Monitoring Wells and Monitoring Points at IR Site 6

Water was discharged to treatment ponds located approximately 200 ft from most of the proposed test wells.

3.1.7 Marine Corps Air Station (MCAS) Cherry Point

MCAS Cherry Point is an 11,485-acre installation north of the town of Havelock in southeastern Craven County, North Carolina. The station is surrounded by water on three sides: Slocum Creek on the west, Hancock Creek on the east, and the Neuse River on the north. MCAS Cherry Point was commissioned in 1942 and the mission is to maintain and operate support facilities, services, and material.

3.1.7.1 Site Location and History

Site 1640 is the location of the air traffic control center and the aircraft boarding gate for MCAS Cherry Point (Figure 3-9). The site contains emergency electrical generators and once had an underground storage tank for the storage of the generator fuel. Over time, leaks and spills from the storage tank resulted in free-phase contamination.

3.1.7.2 Presence of LNAPL and Depth to Groundwater

Routinely, LNAPL has been detected in the site wells ranging from 0.2 to approximately 2 ft thick. The areal extent of the LNAPL contamination is approximately 40 ft × 40 ft. Groundwater is typically encountered between 5 and 8 ft bgs.

3.1.7.3 Type of LNAPL

The existing LNAPL at the site is No. 2 Fuel Oil, which originated from the fuel storage tank.

3.1.7.4 Soil Conditions

From the ground surface to approximately 5 ft below the water table, the soils are composed of fairly homogenous medium-sized sands. Initially, there were concerns about the soil containing a vacuum because of its porosity. However, after starting the bioslurper, reasonable vacuum levels were produced in the wells.

3.1.7.5 Tendency of LNAPL to Form Emulsions

No bioslurper system had been operated at this site previously. Therefore, there was uncertainty about the emulsion-forming potential at the site. However, heating oil generally produces significant emulsions; thus, MCAS Cherry Point was selected as a test site.

3.1.7.6 Logistical Considerations

The logistical considerations were minimal. The LRP was connected to Base power. The recovered groundwater was discharged to the storm sewer after treatment with activated carbon, and the off-gas was discharged directly to the atmosphere.

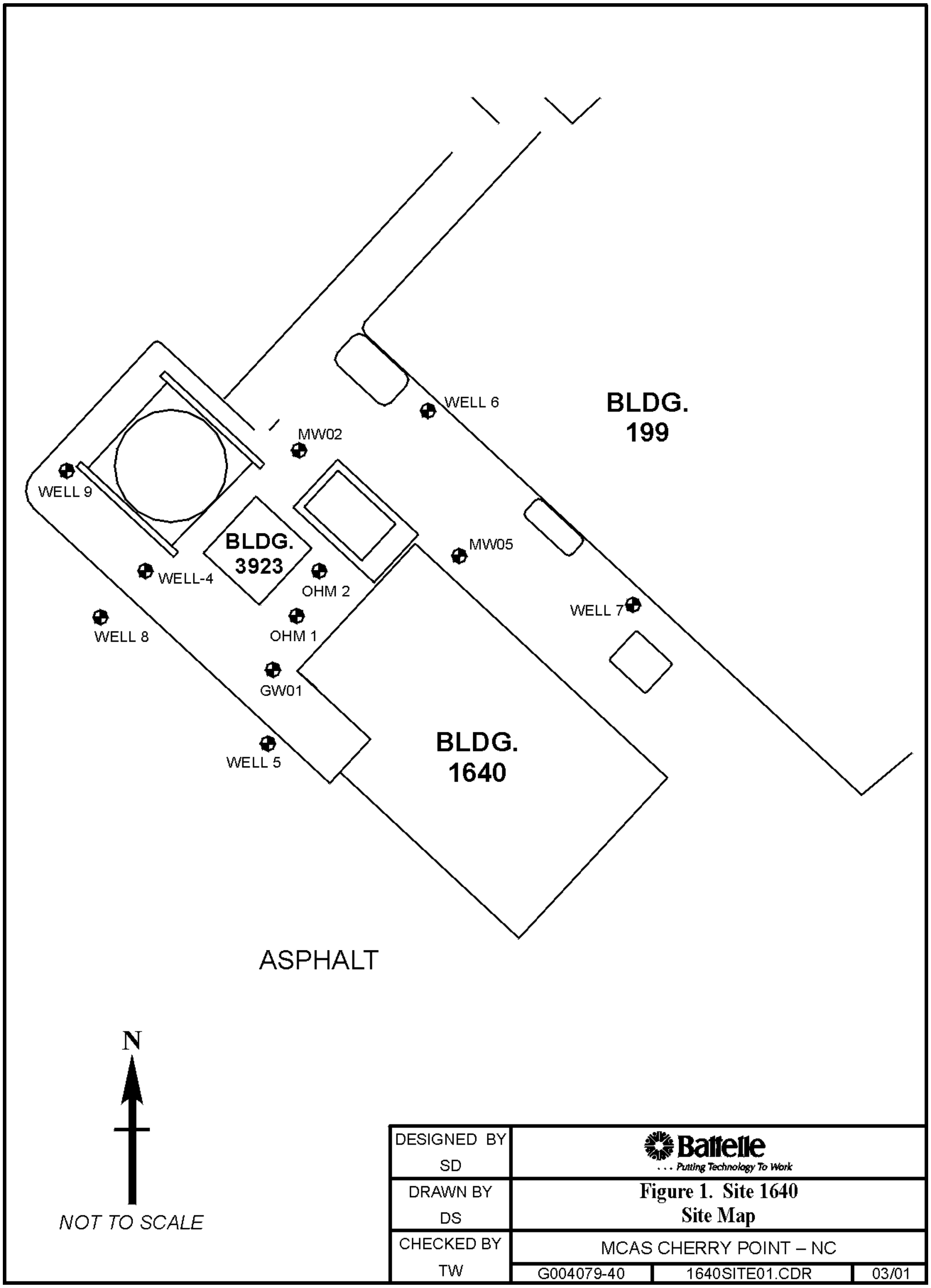


Figure 3-9. Map of Site 1640, MCAS Cherry Point

3.1.8 Hickam Air Force Base (AFB), Hawaii

Hickam AFB is located on the island of Oahu adjacent to Pearl Harbor and the Honolulu International Airport. Information concerning site conditions and background was obtained from an investigation conducted by CH_2M Hill (CH_2M Hill, 2000).

3.1.8.1 Site Location and History

The site is located on the east-central portion of Hickam AFB. It consists primarily of the AMC Ramp, which is used for aircraft cargo loading/unloading, aircraft parking, and fueling. Before the early 1990s, JP-4 jet fuel was distributed from the fuel area to pressurized fueling hydrants at the AMC Ramp for fueling and defueling of military aircraft (Figure 3-10). Since the early 1990s, JP-8 jet fuel has been used for aircraft refueling operations. Suspected sources of contamination are leaks and spills associated with the underground pipelines used to transport the jet fuel.

3.1.8.2 Presence of LNAPL and Depth to Groundwater

Routinely, LNAPL has been detected in the site wells ranging from 2 to approximately 5 ft thick.

Groundwater is typically encountered between 3.5 and 12.4 ft bgs. Tidal fluctuations in the groundwater levels at the site are typically 1.3 ft. Groundwater flow direction is to the south and southwest at an estimated velocity of 0.072 to 0.612 ft per day.

3.1.8.3 Type of LNAPL

The existing LNAPL at the site is JP-4 jet fuel, which originated from leaking pipelines from the fuel area to the AMC Ramp.

3.1.8.4 Soil Conditions

The general geology ranges from concrete at the surface to sands, silts, gravels, and clays to coralline limestone at depths from 3 to 13 ft bgs. The saturated layer is composed of coralline limestone.

3.1.8.5 Tendency of LNAPL to Form Emulsions

Moderate emulsions were formed during previous conventional bioslurping.

3.1.8.6 Logistical Considerations

No power source was located near the site, so a generator was used. The process water was collected in a storage tank before disposal. Air emissions did not need to be treated because of the short duration of the demonstration. A thermal oxidizer was located on site and used to partially treat the off-gas emissions.

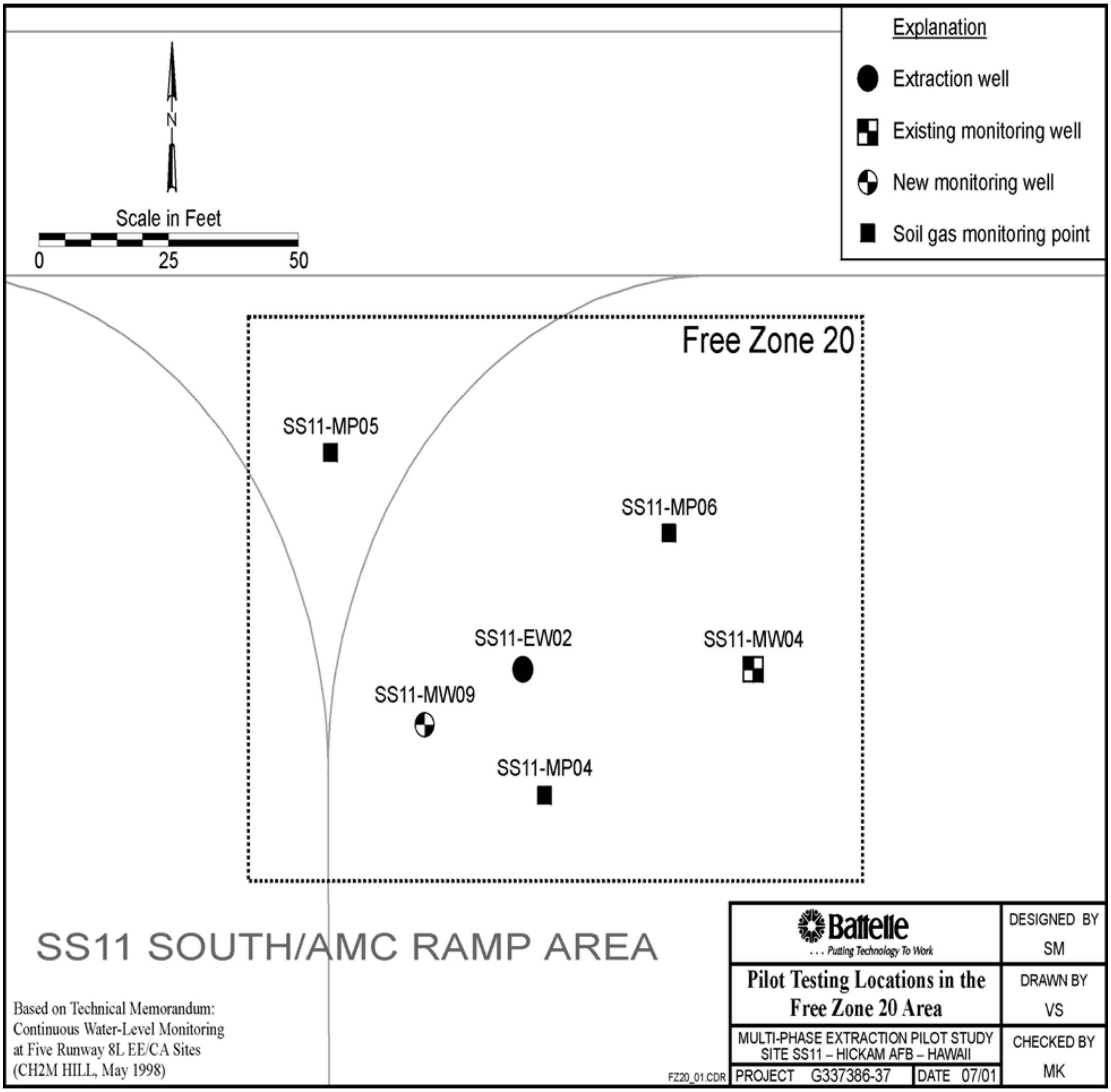


Figure 3-10. Hickam AFB Location of Extraction Well

4.0 Demonstration Approach

4.1 Performance Objectives

The performance objectives provided the basis for establishing the operating parameters of a bioslurper system under which the function and cost-effectiveness of the prepump modifications can be evaluated. The field demonstration was designed for a side-by-side comparison of a bioslurper system using the prepump separation methods and in the conventional configuration. The primary objectives of the short-term demonstrations were to use the prepump separation methods to accomplish the following:

- Eliminate or minimize the formation of stable oil/water emulsions and floating solids
- Evaluate the reduction petroleum hydrocarbon concentrations in the process water
- Evaluate the reduction petroleum hydrocarbon concentrations in the stack gas.

The secondary objectives of the demonstration project are to determine optimal equipment sizing, design, and operational settings of the prepump separation methods, including:

- Sizing and design of the knockout tank
- Sizing of the drop tubes
- Relative depth setting of the LNAPL and groundwater/soil-gas drop tubes
- Vacuum in the LNAPL and groundwater/soil-gas drop tubes.

The objectives for the long-term demonstration included all of the objectives of the short-term demonstrations; however, operational costs in a full-scale configuration were also evaluated during the long-term demonstration.

Because the formation of stable emulsions and floating solids and the operation of the prepump separation methods are site-dependent, the bioslurper system was demonstrated at sites with different site conditions (i.e., type of LNAPL, geology, and hydrogeology). The results of the studies provide an understanding of the variables affecting the operation of the prepump separation methods. Reduced petroleum hydrocarbon concentrations in the process water and stack gas and the elimination of stable emulsions and floating solids were the primary parameters for demonstrating the effectiveness of the prepump separation methods. Additionally, the design and configuration of the prepump separation methods were continuously improved throughout the project period to provide the most appropriate design and settings. The ultimate goals were to eliminate or minimize the formation of emulsions and significantly reduce the concentrations of petroleum hydrocarbons in the process water and stack gas streams without additional labor compared to the conventional bioslurper operation.

4.2 Demonstration Setup and Operation

Specific tests were performed to quantitatively assess the operation of the bioslurper system and evaluate the formation potential of stable emulsions and floating solids. Sampling and analyses were carried out to demonstrate decreases in petroleum hydrocarbon concentrations in the process water and stack gas streams. During the long-term demonstration the labor requirements for each operational configuration were recorded to assess the cost-effectiveness of the prepump

separation systems. This section describes the procedures and protocols that were used during the demonstrations. In addition, the information gained by these tests and sampling activities is discussed.

4.2.1 System Design

The bioslurper system used for the demonstrations was designed to allow convenient and quick conversion from one configuration of the bioslurper to another. For example, the extraction manifolds, liquid ring pump, and OWSs of the systems were thoroughly cleaned to avoid cross contamination when used to perform prepump separation options. If the thoroughness of the cleaning was in question, the materials were replaced for each phase of the demonstration. At most of the sites a bioslurper system was not at the site; therefore, a mobile bioslurper unit was mobilized to the site for the demonstration. Figure 4-1 contains the schematic of a mobile bioslurper system. Figure 4-2 shows a photograph of the mobile bioslurper system at Bolling AFB.

The bioslurper systems used during the demonstrations were equipped with a liquid ring pump to produce vacuum and extract LNAPL, groundwater, and soil gas. The systems also used an OWS equipped with coalescer media after the liquid ring pump to prevent the discharge of LNAPL during the final disposal of the process water. The mobile unit constructed for this demonstration had the prepump separation configurations attached to the trailer.

4.2.2 General Short-Term Demonstration Operation

The testing sequence successfully monitored the effects of prepump separation systems and LNAPL and groundwater recovery on the emulsion formation and contaminant discharge. The testing sequence also was scheduled to prevent disturbance to the aquifer from one test to another. Table 4-1 presents the sequence of the tests performed at each short-term demonstration site. After the mobilization and system setup at a site, the bioslurper system was operated for a series of four tests, each lasting for about four days. The duration of the tests at Tyndall AFB were shortened to 48 hours because of the low LNAPL-recovery rate. The durations of the tests at MCAS Cherry Point and Hickam AFB were shortened because of scheduling conflicts at the site. At NAWC China Lake, two tests of the dual drop tube were performed to optimize performance of the system. During the initial test, LNAPL recovery into the well was greater than the extraction rate by the bioslurper system. The LNAPL thickness eventually exceeded the length of the shield, and was extracted in the groundwater/soil gas stream. The dual drop tube test was later repeated successfully with a longer shield and an increased diameter fuel extraction tube. At all of the demonstration sites, the testing sequence began and ended with the test using the conventional single drop tube configuration to provide baseline operating conditions of the conventional bioslurper over the duration of demonstration. Testing of the knockout tank and dual drop tube systems was conducted between the two conventional bioslurper tests. However, the knockout tank was not tested at MCAS Cherry Point, NFD Point Molate, and Hickam AFB due to its limited efficiency at previous test sites. Generally, the bioslurper system was operated 24 hr/day during each test. Downtimes occurred when the system was being cleaned and reconfigured between tests and for maintenance of the system.

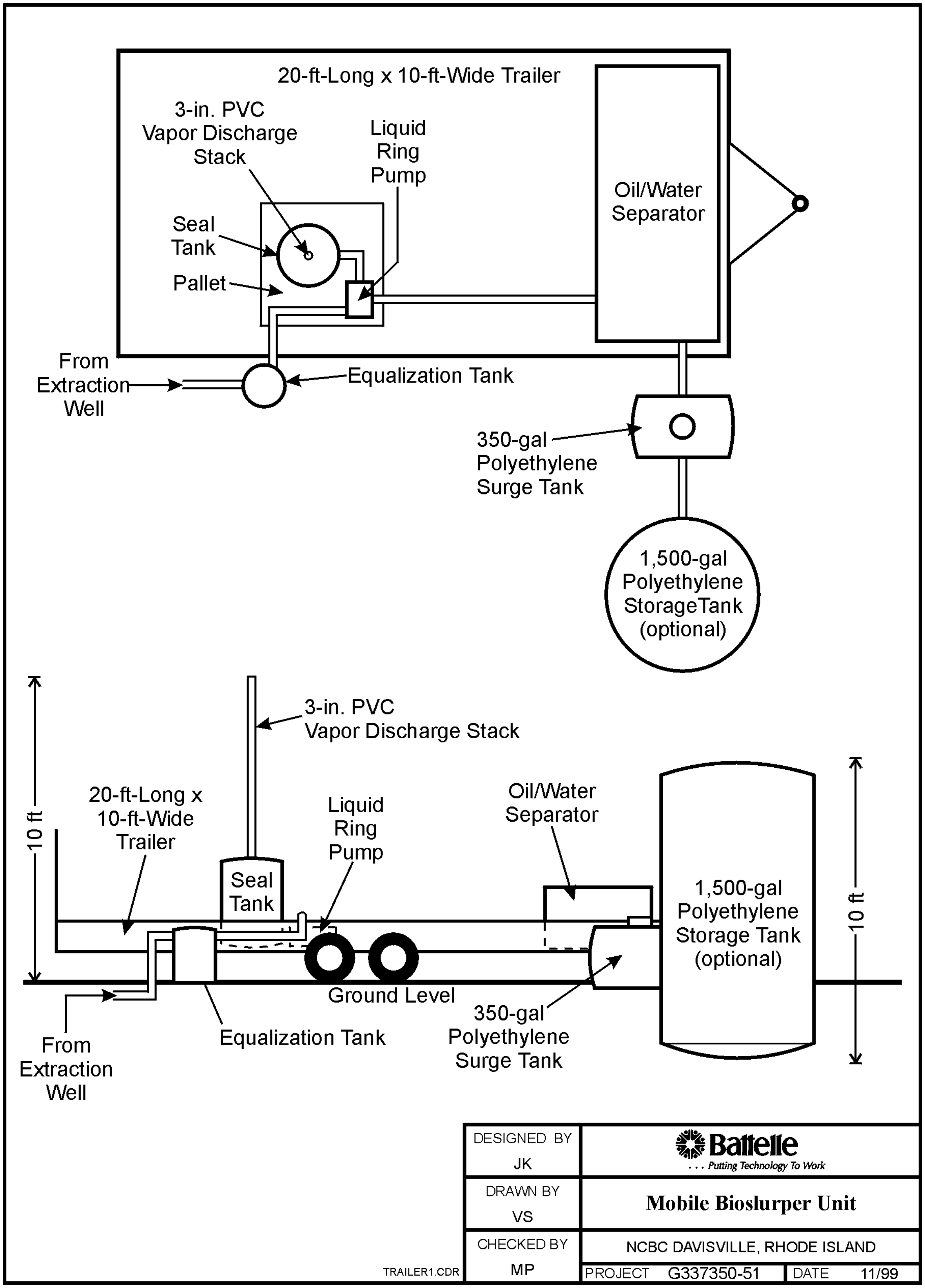


Figure 4-1. Schematic Diagram of a Mobile Bioslurper System

Figure 4-2. Photograph of Mobile Bioslurper System at Bolling AFB

Following each test, LNAPL was removed from the system and quantified, the tanks and separators were drained, and the bioslurper system was thoroughly cleaned with soapy water to prevent carryover of petroleum hydrocarbons from one test to another. After cleaning, the pump and separator was reprimed with tap water so the LNAPL and groundwater recovery rates could be accurately quantified. Subsection 4.2.3 describes the general protocol that was followed, methods for generating the data, and the analytical procedures used during the short-term demonstrations.

Table 4-1. Testing Sequence at Each Demonstration Location

Site Location	Test Duration (Hours)			
	1st Conventional	Dual Drop tube	Knockout Tank	2nd Conventional
NCBC Davisville	98	96	78	96
NAS Fallon – 48 Hour	48	48	48	48
NAS Fallon – 1 Week	120	120	120	120
Bolling AFB	72	72	72	72
NAWC China Lake	72	72	72	72
Tyndall AFB	48	48	48	48
NFD Point Molate	72	72	Not Tested	36
MCAS Cherry Point	31	47	Not Tested	36
Hickam AFB	72	72	Not Tested	72

4.2.3 Sampling and Analytical Procedures

4.2.3.1 Measurement of Baseline Parameters

The following baseline parameters were measured prior to short-term demonstrations (if soil gas monitoring points were available) or, if available, obtained from predemonstration activities:

- Depth to groundwater and LNAPL thickness in the proposed extraction well
- Soil-gas composition (i.e., O_2, CO_2, and TPH)
- Subsurface vacuum.

The depth to groundwater and apparent thickness of LNAPL in monitoring wells were measured using an oil/water interface probe, which distinguishes polar and nonpolar fluids in the wells. This probe gives a solid tone when it encounters a nonpolar liquid (e.g., LNAPL) and a constant beep when it encounters a polar liquid (e.g., groundwater). The probe lead is a 50- to 200-ft measuring tape marked at 0.01-ft increments. Available historical LNAPL and groundwater level data were evaluated to determine if temporal variations occur in the interface readings.

Soil-gas composition provides information regarding the degree of contamination in the vadose zone and can be used to determine potential background concentrations of petroleum hydrocarbons in the stack gas stream. If soil-gas monitoring points were present near the proposed extraction well, these points were used to measure the concentrations of oxygen, carbon dioxide, and TPH. Calibrated handheld meters were used to measure the composition of the soil gas.

Subsurface pressure monitoring provides a method to estimate the radius of influence from the extraction well that is produced by the bioslurper system. If soil gas monitoring points were present at the site, subsurface pressure measurements were made with a series of low-level vacuum gauges and the vacuum was recorded in inches of water. Throughout the testing at each demonstration site, the subsurface vacuum was monitored to produce vacuum vs. distance curves, which then was used to estimate the vadose zone radius of influence.

Baseline data also were collected when the bioslurper system was operated in the conventional configuration. System operating parameters such as LNAPL-recovery rate, groundwater recovery rate, emulsion production, and petroleum hydrocarbon concentration in the process water were measured to provide baseline data for the conventional bioslurper system.

4.2.3.2 System Performance Parameters

Following the measurement of baseline parameters, the field tests were initiated. Key parameters that were measured or monitored include:

- Petroleum hydrocarbon concentrations in the seal water reservoir (designated as seal water samples) and the discharge water from the OWS unit of the bioslurper system (designated process water samples)

- Petroleum hydrocarbon concentrations in the stack-gas stream from the liquid ring pump (not collected at NFD Point Molate and MCAS Cherry Point)

- Emulsions and floating solids formed

- LNAPL-recovery rate

- Groundwater-recovery rate

- Stack gas flowrate

- Vadose zone radius of influence.

Samples of the bioslurper process water and stack gas streams were routinely collected during each test. The process water samples were analyzed for TPH and BTEX. After the second short-term demonstration (NAS Fallon) was conducted, it was determined that the BTEX analyses did not provide significant information and the remainder of the demonstrations were conducted without BTEX analyses. Petroleum hydrocarbon concentrations in the stack gas were measured using a calibrated, handheld meter. Additionally, confirmatory samples of the stack gas were collected for laboratory analysis. Sampling methods and sampling frequency are presented below.

Samples of the bioslurper process water were collected routinely during each test from the OWS effluent port. Process and seal water samples were collected every 24 hours during tests with a duration of 72 or less and at 24, 48, and 96 hours after the testing began for tests of 96 hours in length (Table 4-2). The water was collected in 40-mL VOA vials, labeled with sample identification (ID) numbers, placed on ice, and shipped via express delivery to the laboratory for analysis. The number of vials collected was dependent on the type of fuel present at the site and the analyses that was requested.

The seal water, process water and groundwater samples were analyzed for TPH purgeable, TPH extractable and BTEX depending on the site (Table 4-3). TPH purgeable and BTEX were analyzed using a purge-and-trap technique followed with mass spectrometry/gas chromatography

Method SW-8260. The TPH extractable was analyzed using Method SW-8015 modified for the predominant fuel type and an extraction technique followed with a gas chromatograph equipped with a photoionization detector. Due to the high levels of petroleum hydrocarbons in the seal and process water samples collected during operation in the conventional configuration, a special extraction process was performed by the laboratory to accurately quantify the total concentration of petroleum hydrocarbons.

Table 4-2. Sampling Schedule During Each Test

Sample Type	Sample Location	Sampling Frequency
Groundwater	Extraction well through drop tube	Prior to initiating testing phases
Process water	OWS effluent sampling port	24, 48, and 96 hours
Discharge water	Point of discharge	As required by regulators
Stack gas with handheld meter	Sampling port in off-gas stack	2, 4, 8, 12, and 24 hours following startup; daily thereafter
Stack gas with Summa canisters	Sampling port in off-gas stack	48 and 96 hours
Emulsions and floating solids	In OWS	2, 4, 8, 12, 24, 48, 72, and 96 hours following startup

Table 4-3. Suggested Sampling and Analytical Methods

Analysis	Analytical Method	MDL	Container	Sample Size	Preservation Technique	Holding Time
Groundwater						
TPH (P)	SW-8260	0.5 mg/L	Borosilicate glass VOA vials	3 x 40-mL	HCl to pH <2 @ 4^{o}C	14 days
TPH (E)	SW-8015	0.5 mg/L	Amber glass bottle	1 to 2 L	Cool @ 4^{o}C	14 days to extraction
Pump/OWS Effluent Water						
TPH (P)	SW-8260	0.5 mg/L	Borosilicate glass VOA vials	3 x 40-mL	HCl to pH <2 @ 4^{o}C	14 days
TPH (E)	SW-8015	0.5 mg/L	Amber glass bottle	1 to 2 L	Cool @ 4^{o}C	14 days to extraction
Stack Gas						
BTEX	EPA TO-3	1.0 ppbv	Summa canister	1-L	NA	30 days
TPH	EPA TO-3	10.0 ppbv	Summa canister	1-L	NA	30 days
TPH w/ Meter	NA	NA	Handheld meter	NA	NA	NA

TPH (P) = purgeable total petroleum hydrocarbons.
TPH (E) = extractable total petroleum hydrocarbons.
HCl = hydrochloric acid.
MDL = method detection limit.
NA = not applicable.
ppbv = parts per billion by volume.

Sampling and analysis of the discharge water from the bioslurper system was required by the regulatory agencies at NCBC Davisville, Bolling AFB, NAWC China Lake and MCAS Cherry Point. These samples were collected at the bioslurper's point of discharge. The regulatory requirements dictated the number of samples collected and the constituents analyzed.

TPH concentrations in the stack gas were quantified using a calibrated, handheld meter at 2, 4, 8, 12, and 24 hours after the start of each test. After 24 hours, the TPH was monitored on a 24-hour interval. Stack gas was routinely monitored using a handheld meter (GasTech or equivalent), which measures TPH concentrations in vapor streams using a hot wire sensor. The measurements were done by connecting the field meter directly to the stack until the TPH concentration stabilized (to within ±10 parts per million [ppm]). The meter was calibrated using a 4,800-mg/L hexane standard immediately before use.

To validate the stack-gas measurements using the handheld meter, stack-gas samples were collected in a 1-L, evacuated, polished stainless steel, Summa air-sampling canisters. Two samples of the off-gas were collected during each testing phase (Table 4-2). During the demonstrations at NCBC Davisville, NAS Fallon, Bolling AFB, and NAWC China Lake the samples were collected simultaneously with the field measurements. These samples accurately measured the concentrations of TPH in the off-gas at the short time of sampling (approximately three minutes). During the demonstration at Tyndall AFB the Summa canisters were equipped with a device to allow the sample to be collected over a 24-hour period. Prior to sampling, the sampling line was flushed with the off-gas pulled from the stack by a vacuum pump. To collect a sample, the valve on the canister was opened, allowing the vacuum in the canister to be displaced with the vapor sample until atmospheric pressure was reached. The vacuum/pressure in each canister was confirmed before and after each sampling event to ensure that the canister was received at the test site in an evacuated state and was filled completely during sampling. The samples were sent to the analytical laboratory via overnight express and analyzed using Method TO-3 (Table 4-3).

The formation of stable emulsions and floating solids were monitored to evaluate the effectiveness of the prepump separation methods. Samples of the floating solids were collected 2, 4, 8, 12, 24, 48, 72, and 96 hours after the startup of the demonstration (Table 4-2). The appearance of the emulsions and floating solids formed in the OWS and the OWS effluent stream were recorded and photographed. Samples of the emulsions and floating solids in the OWS were collected using a bailer-style sampling device. Samples from the seal water reservoir (i.e., seal water) and the OWS effluent stream (i.e., the process water) were collected periodically for quantitative and qualitative evaluation of the emulsions.

At Davisville, the LNAPL-recovery rate was estimated by measuring the thickness in the OWS. Capability in the thickness of the LNAPL layer led to capability LNAPL-recovery readings. The LNAPL recovery rate was periodically monitored throughout each test. The monitoring frequency varied during the testing (i.e., more frequent monitoring was performed at the beginning of the test). This was done to distinguish between the removal of LNAPL from the extraction well and sand pack and the removal of LNAPL from the soil formation. The LNAPL recovery rate was used to determine if either of the prepump separation methods had an effect on the removal of LNAPL from the subsurface.

The LNAPL recovered was quantified as it was transferred from the oil reservoir for the OWS or the prepump separators to a large holding tank. The fuel transfer was done using a hand-operated drum pump when the conventional bioslurper system was tested. When the dual drop tube configuration was tested, the LNAPL was quantified when it was transferred from the liquid/vapor separator to the fuel storage tank. During the knockout tank testing, the recovered LNAPL was measured as it flowed from the knockout tank to the fuel storage tank. In all cases, the recovered volumes were quantified using an in-line flow-totalizer meter. The recovered volumes were measured on a daily basis. This procedure made it possible to differentiate the initial LNAPL recovery from the sustainable LNAPL recovery.

The groundwater recovery rate was measured periodically during each phase of the demonstration. The groundwater recovery rate and the analytical data were used to determine if a correlation could be made between the groundwater recovery rate and the effectiveness of the prepump separation systems. The groundwater recovery volume was monitored continuously using an in-line flow totalizer. However, the groundwater recovery rate was recorded at least every 12 hours.

Groundwater samples were collected prior to initiating the first test of the demonstration to provide background concentrations of petroleum hydrocarbons. Results of the groundwater analyses were compared to those for the process water to indicate the degree of emulsification produced by the bioslurper process.

The stack-gas flowrate was measured periodically throughout the tests using a pitot tube air flowmeter. The flowrate was combined with the concentrations of petroleum hydrocarbons in the off-gas to calculate the discharge rate of hydrocarbons in mass/day. The contaminant discharge rates for the four tests of the demonstration were compared to evaluate the effectiveness of the prepump separation methods.

The flowrate of the stack gas was quantified using a pitot tube (Annubar Flow Characteristics Model #HCR-15 or equivalent) flow indicator. The stack-gas flowrate was recorded at least every 12 hours and when composition of the stack gas was monitored. The pitot tube was connected to a differential pressure gauge calibrated in inches of water. The flowrate in ft^3/min (cfm) was determined by referencing the differential pressure to a flow calibration curve.

The volume of the vapor discharge was calculated based on the average flowrate and the time of operation. The mass of petroleum hydrocarbons extracted in the vapor phase was calculated based on the average concentration of TPH in the stack gas and the volume released.

A vadose zone radius-of-influence test was performed at the demonstrations at Bolling AFB, NFD Point Molate, and Hickam AFB. The vacuum produced in the extraction well radiates into the vadose, capillary, and saturated zones of the formation. The vadose zone radius of influence is calculated using the magnitude of the vacuum in soil-gas monitoring points at various distances from the extraction well. The soil-gas pressure was measured about every two hours until the change in pressure was less than 0.1 inch of H_2O. The pressure versus distance data were then plotted on an x-y plot, and a line was fitted through the data. The intersection of the line with the 0.1-inch H_2O vacuum is considered the vadose zone radius of influence.

Monitoring of the soil-gas composition was performed on a regular basis during the demonstrations at Bolling AFB, NFD Point Molate, and Hickam AFB using soil-gas monitoring points. The soil-gas composition data were used to evaluate how oxygen, carbon dioxide, and TPH concentrations in the soil gas vary with time. Further, in conjunction with the results of any in situ respiration data, the soil-gas monitoring data may be used to estimate the mass of petroleum hydrocarbons removed from the vadose zone through biodegradation (in mg TPH/kg of soil/year). Using *n*-hexane as a model compound for TPH, a stoichiometric equation describing hydrocarbon degradation may be presented as follows:

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O \qquad (1)$$

Based on this equation, approximately 3.5 g of oxygen is required, on a weight basis, for every 1 g of hydrocarbon consumed. Therefore, the hydrocarbon degradation rate is approximately 0.29 times the oxygen utilization rate on a weight basis.

4.2.4 Long-Term Test Sequence

Similar to the short-term demonstration, the testing sequence of the long-term demonstration was designed to monitor the effects of prepump separation systems on the LNAPL and groundwater recovery and on the emulsion formation and contaminant discharge. However, the long-term demonstration was focused on the effects of multiple well operation of the prepump separation systems. Additionally, the long-term demonstration data were used to evaluate the cost performance of the prepump separation systems relative to operation in this conventional configuration. Table 4-4 presents the sequence of the tests performed during the long-term demonstration. After the mobilization and system setup at a site, the bioslurper system was operated for approximately four months in different configurations to assess the capability of the prepump separation systems. The testing sequence began and ended with the test using the conventional single drop tube configuration to provide baseline operating conditions of the conventional bioslurper over the duration of demonstration. All the testing of the knockout tank and dual drop tube systems was conducted between the two conventional bioslurper tests. Operation of the dual drop tube system was initiated with a single well, and wells were gradually added to determine if the number of wells would affect the system operation. The dual drop tube system was operated with the knockout tank for the longest period of time because it was believed that this configuration would be the most effective configuration at reducing the petroleum hydrocarbon concentrations in the discharge streams. Also, it was believed that this configuration would increase the life of the bioslurper equipment by the reduction of the slugging action by the knockout tank. Although the operation of the knockout tank alone did not perform exceptionally well during the short-term demonstrations, it was decided that it should be tested during the long-term demonstration to evaluate the cost performance of the system. Generally, the bioslurper system was operated 24 hr/day during each test. Downtimes occurred when the system was being cleaned and reconfigured between tests, for maintenance of the system. Freezing conditions near the end of the long-term demonstration (during the dual drop tube with knockout tank test) forced the unexpected shutdown of the bioslurper unit.

Table 4-4. Long-Term Testing Sequence at NAS Fallon

Bioslurper System Configuration	Test Duration
Mobilization to the demonstration site and system setup	4 days
Conventional single drop tube configuration	7 days
Dual drop tube configuration	14 days
Single well	3 days
Two wells	3 days
Five wells	8 days
Dual drop tube configuration with knockout tank	54 days
Single drop tube configuration plus the knockout tank	14 days
Conventional single drop tube configuration	7 days
Demobilization from the demonstration site	2 days

5.0 Performance Assessment

5.1 Performance Data

The performance of the prepump separation systems was based primarily on the petroleum hydrocarbon concentrations in the vapor and aqueous streams. The analytical data generated while operating in the dual drop tube and knockout tank configurations were compared to those data generated while operating in the conventional configuration. All of the testing performed during the short-term demonstrations was conducted at a single well to provide a side-by-side comparison of the technologies being tested. A secondary evaluation of system performance was performed by sampling the liquid stream in the bioslurper system for the presence and consistency of floating solids. An example of the measurement of the floating solids at Tyndall AFB, Florida, can be seen in Figure 5-1. Photographs were taken of the liquid stream so that the degree of emulsification could be compared. In Figure 5-2, a photograph was taken to compare the degree of emulsification of the seal tank water and process water for (from left to right) conventional, dual drop tube, and knockout tank configurations. A sample of the floating solids was taken during each configuration that floating solids were formed. This sample was centrifuged to determine the ratio of solids, fuel and water. The sample was also sent to an analytical lab for analyses of suspended solids, oil & grease, calcium, manganese, iron, and aluminum.

Figure 5-1. Volume Measurements Aqueous Stream with Emulsified Fuel in Water, Floating Solids and Relatively Clean Fuel

Figure 5-2. Comparison of Aqueous Streams During Knockout, Dual Drop tube and Conventional Tests (L to R)

Baseline data were collected from the operation of the bioslurper system in the conventional configuration prior to and after the operation of the prepump separation systems. Typically, the LNAPL-recovery rate decreases as the bioslurper operational time increases, and concentration of petroleum hydrocarbons in the aqueous and vapor discharge streams is related to the LNAPL-

recovery rate. Therefore, conducting tests of the conventional bioslurper before and after operation of the prepump systems allows for the comparison of data from similar testing operational conditions (i.e., LNAPL and groundwater-recovery rates). If necessary, corrections to the petroleum hydrocarbon concentrations could be made to account for the LNAPL or groundwater-recovery rates. In addition, groundwater samples were collected from the recovery well being used to determine the baseline concentrations of the petroleum hydrocarbons in the groundwater. These concentrations were used to determine the degree of petroleum hydrocarbon emulsification produced by the operation of the bioslurper in the different configurations.

Additional data were collected to assess if the prepump separation systems affected the performance of the bioslurper systems. For example, LNAPL and groundwater-recovery rates were measured throughout each test phase to determine if prepump separation systems increase or decrease the LNAPL or groundwater-recovery rates. At sites that contained soil gas monitoring points, the composition of the soil gas was monitored throughout the demonstration to obtain baseline petroleum hydrocarbon levels in the gas stream and to determine if the operation of the systems increased the petroleum hydrocarbon concentrations in the vapor phase. In addition, the soil gas monitoring points (if present) were used to estimate the vadose zone radius of influence. The radii of influence in the different configurations were then compared to determine if the prepump separation systems affect the vadose zone radius of influence.

When possible, the prepump separation systems were modified to determine the effects of the modifications and to improve the design of the systems. For example, the length of the LNAPL shield on the dual drop tube was lengthened during the demonstration at NAWC China Lake. The diameter of the LNAPL-extraction tube was increased during the demonstrations at NAWC China Lake, and Hickam AFB in an attempt to improve LNAPL recovery rates. Also, intermittent LNAPL extraction from the extraction well during operation in the dual drop tube testing phase was investigated at NCBC Davisville, Bolling AFB, Tyndall AFB, and NFD Point Molate. Intermittent LNAPL extraction was investigated to determine most efficient operational conditions of the dual drop tube system. Two different knockout tank configurations were tested during the demonstration to determine the more appropriate configuration.

5.1.1 Performance Data from the Short-Term Demonstration Sites

Short-term demonstrations were performed at eight sites. Appendix B-1 contains the groundwater, fuel, and floating solids recovery tables and graphs for each short-term demonstration. Appendix B-2 presents the groundwater, process water, seal-tank water, and off-gas analytical results tables for each short-term demonstration. Appendix B-3 contains the raw analytical sheets.

5.1.1.1 Performance Data from NCBC Davisville, Rhode Island

Table 5-1 details the operational data at NCBC Davisville, Rhode Island. The fuel recovery rate rapidly decreased throughout the extraction test at each well to a degree that the LNAPL was completely removed from the three wells (EW-4, EW-8, and EW-7) used during the demonstration. This depletion necessitated moving to three different wells during the demonstration and using two different wells when the second conventional configuration test was being performed. During the entire demonstration, approximately 57 gallons of LNAPL were extracted from the subsurface.

Table 5-1. Operational Data at NCBC Davisville, RI

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Solids Recovered (gal)	Fuel Recovered (gal)
1st Conventional (EW-4)	98	1,317.5	3.54	15.93
Knockout Tank (EW-8)	78.4	501.4	1.33	37.87
Dual Drop tube (EW-7)	96	258.69	0.55	3.45
2nd Conventional (FW-4/EW-8)	95.9	493.7	2.21	0
Cumulative bioslurper operation	368.3	2,571.29	7.63	57.25

Figure 5-3. Photo of Fuel Floating Solids and Water at NCBC Davisville

The groundwater-recovery rates were relatively low and relatively constant throughout each phase of the demonstration; however, the groundwater recovery rate was significantly higher when operating at EW-4. The average groundwater recovery rate during the knockout tank, dual drop tube and the first part of the second conventional test was less than 0.1 gpm, while the average groundwater recovery rate when operating at EW-4 was approximately 1 gpm.

The recovery rate of the floating solids was estimated by measuring their thickness in the OWS. The volume of floating solids recovered during each phase of the demonstration was relatively consistent. Depending on the phase of the test, the floating solids compose between 3% and 100% of the organic liquid recovered. The proportion of floating solids in the organic liquids was lowest with the operation of the dual drop tube and knockout tank systems (3 to 16%), while the fraction of floating solids in the organic liquid was greatest (22 to 100%) when the conventional configuration was being tested. Table 5-2 shows the analytical results of the solids samples that were taken during the first conventional configurations.

Table 5-2. Solids Analytical Results at NCBC Davisville, RI

Sample ID	Suspended Solids (mg/L)	Ca (mg/L)	Mg (mg/L)	Grease-Hydrocarbon Content (mg/L)	Oil and Grease (mg/L)	Al (mg/L)	Fe (mg/L)
Davis-FS-1	17,010	87	27	ND	ND	270	960
Davis-FS-2	28,850	130	38	ND	ND	400	1,200

ND = nondetect

Table 5-3 presents the process water analytical summary for NCBC Davisville, Rhode Island. The average TPH-E concentrations in the process water for the first conventional, knockout tank, dual drop tube, and second conventional configuration were 22, 44, 23, and 19 mg/L, respectively.

Table 5-3. Process Water Analytical Summary at NCBC Davisville, RI

Test Configuration	Avg. TPH-E (mg/L)	Avg. TPH-P (mg/L)	Avg. Benzene (μg/L)	Avg. Toluene (μg/L)	Avg. Ethylbenzene (μg/L)	Avg. Xylenes (μg/L)
1st Conventional (EW-4)	22	1.5	ND	1.1	27	162
Knockout Tank (EW-8)	44	4.1	ND	ND	33	320
Dual Drop Tube (EW-7)	23	3.0	ND	ND	33	281
2nd Conventional (EW-4/EW-8)	19	1.2	ND	ND	29	217

The stack gas discharge rates were nearly the same when the first conventional, knockout tank, dual drop tube, and second conventional were being operated. The discharge rate was approximately 31 scfm throughout the demonstration. Table 5-4 presents the off-gas analytical summary for NCBC Davisville, Rhode Island. The average TPH concentration in the off-gas during the first conventional, knockout tank, dual drop tube, and second conventional tests were 720, 255, 240, and 260 ppmv, respectively.

Table 5-4. Off-Gas Analytical Summary at NCBC Davisville, RI

Test Configuration	TPH (C5+) (ppmv)	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)
1st Conventional (EW-4)	720	0.53	2.6	8.8	27
Knockout Tank (EW-8)	255	0.16	0.78	2.7	8.5
Dual Drop Tube (EW-7)	240	ND	0.58	1.4	5.9
2nd Conventional (EW-4/EW-8)	260	0.03	0.5	1.28	5.2

Two baildown tests were conducted at NCBC Davisville to provide a qualitative indication of the presence of mobile, free-phase LNAPL and its recovery potential. The first baildown test, which was conducted at extraction well EW-3 (see Figure 3-2), indicated a relatively slow rate of LNAPL recovery into the well and resulted in an LNAPL thickness of approximately half of the initial apparent thickness after a 12-hour period. The second baildown test on the same well resulted in approximately two-thirds of the initial apparent LNAPL thickness after an 8-hour period. These data indicate that the LNAPL present at the site has a low mobility under passive conditions and therefore was relatively difficult to recover.

Two soil-gas permeability tests were conducted concurrently with the startup of the bioslurper pump. The vadose zone radius of influence was calculated by plotting the log of the average vacuum level at the monitoring points versus the distance from the extraction well. The radius of influence then was defined as the distance from the extraction well where 0.1 inch of H_2O can be measured. Based on this definition, the radius of influence during the bioslurper pump test was approximately 22 ft. The second soil-gas permeability test had a radius of influence of approximately 43 ft.

5.1.1.2 Performance Data from NAS Fallon, Nevada

Table 5-5 details the operational data at NAS Fallon, Nevada. During the demonstration at NAS Fallon, there was enough LNAPL recovered to perform two separate tests. One test lasted approximately 48 hours for each configuration. The other test, which followed the 48-hour test, lasted approximately one week for each configuration. Over the course of the demonstration, approximately 2,132 gallons of LNAPL was extracted from the subsurface. Of this, approximately 1,161 gallons of LNAPL was recovered during the 48-hour test, and approximately 971 gallons was recovered from the one-week test. Both the 48-hour test and the 1-week test were performed on well 6T1-11.

During the 48-hour test, the fuel recovery rates were relatively constant throughout each phase of the demonstration, but they decreased over the total period of the 48-hour test demonstration. The average LNAPL recovery rate during each phase of the test ranged from approximately 65 to 246 gallons per day (gpd). The total amount of fuel recovered during the 48-hour test was approximately 1,161 gallons.

Table 5-5. Operational Data at NAS Fallon, NV

Test Configuration		Test Duration (hrs)	Water Recovered (gal)	Fuel Recovered (gal)
48 Hour Test	1st Conventional	43.3	11,459.9	444.5
	Knockout Tank	51.2	13,903.5	334.5
	Dual Drop tube	47.6	12,296.5	243.5
	2nd Conventional	51.3	12,179.7	139.0
	Cumulative bioslurper operation	193.4	49,839.6	1,161.5
1 Week Test	1st Conventional	124.1	22,430.6	407.5
	Knockout Tank	120.2	21,330.1	230.5
	Dual Drop tube	121.5	17,946.1	192.5
	2nd Conventional	122.6	22,295.7	140.5
	Cumulative bioslurper operation	488.4	84,002.5	971
	Total bioslurper operation	681.8	133,842.1	2,132.5

The fuel recovery rates decreased over the duration of the one-week test, but were relatively constant during each phase of the demonstration. The fuel recovery rates during the knockout tank, dual drop tube and second conventional or conventional tests were similar and less than the fuel recovery rate during the first conventional test. The average LNAPL recovery rate during each phase of the test ranged from approximately 27 to 79 gpd. The total amount of fuel recovered during the one-week test was approximately 971 gallons.

The groundwater recovery rates were relatively constant throughout the 48-hour test. The average groundwater recovery rate during the 48-hour test was approximately 4 gpm, and nearly 50,000 gallons of groundwater was recovered during the 48-hour test.

The groundwater recovery rate during the one-week test was nearly constant at a rate of approximately 3 gpm. However, the groundwater recovery rate was less during the dual drop tube test. The total amount of groundwater recovered during the one-week test was approximately 83,000 gallons.

Floating solids were not produced in significant quantities in any of the configurations, but the knockout tank and dual drop tube systems appeared to reduce the production of the by-products. Table 5-6 details the analytical results from the solids sample that was taken during the conventional configuration.

Table 5-6. Solids Analytical Results at NAS Fallon, NV

Sample ID	Moisture Content (%)	Calcium (mg/kg)	Magnesium (mg/kg)	Aluminum (mg/kg)	Iron (mg/kg)	Sample Composition (% by Volume)	
						Oil	Solid & Water
Fallon-FS-1	86	5,300	2,300	360	39,000	68	32

Table 5-7 displays the contaminant concentrations in the process water (after the OWS) and the seal-tank water samples for both the 48-hour test and the one-week test. The average concentrations of TPH-E in the process water during each phase of the 48-hour test are 755, 235, 17, and 870 mg/L during the first conventional, knockout tank, dual drop tube, and second conventional bioslurping tests, respectively. In the seal water tank, the average concentrations were 1,500, 56, and 4,750 mg/L during the knockout tank, dual drop tube, and second conventional bioslurping tests, respectively.

Contaminant concentrations in process water and seal water tank samples for the one-week test are presented in Table 5-7. The average concentrations of TPH-E in the process water during each phase are 463, 437, 14, and 670 mg/L during the first conventional, knockout tank, dual drop tube, and second conventional bioslurping tests, respectively. In the seal water tank, the average concentrations were 6,267, 1,700, 10, and 4,233 mg/L during the first conventional, knockout tank, dual drop tube, and second conventional bioslurping tests, respectively.

Table 5-7. Process Water and Seal-Tank Water Analytical Summary at NAS Fallon, NV

Test Configuration	Avg. TPH-E (mg/L)	Avg. TPH-P (mg/L)	Avg. Benzene (µg/L)	Avg. Toluene (µg/L)	Avg. Ethylbenzene (µg/L)	Avg. Xylenes (µg/L)
48-Hour Test						
1st Conventional - Seal Water Tank	NA	NA	NA	NA	NA	NA
- Process Water	755	16	225	140	110	475
Knockout Tank - Seal Water Tank	1,500	15	330	260	150	640
- Process Water	235	9.2	305	225	120	540
Dual Drop tube - Seal Water Tank	56	4.3	140	83	49	189
-Process Water	17	4.8	130	80	53	186
2nd Conventional - Seal Water Tank	4,750	11	165	195	140	595
- Process Water	870	6	155	170	110	500
1-Week Test						
1st Conventional - Seal Water Tank	6,267	14	143	217	177	770
- Process Water	463	14	127	165	95	545
Knockout Tank - Seal Water Tank	1,700	14	96	135	105	437
- Process Water	437	13	93	128	97	462
Dual Drop tube - Seal Water Tank	10	7	45	56	35	153
- Process Water	14	6	43	45	33	135
2nd Conventional - Seal Water Tank	4,233	13	36	84	85	400
- Process Water	670	11	33	71	64	357

NA = Not available

During the one-week test, the stack gas discharge rates were nearly the same for the first conventional, knockout tank and dual drop tube (approximately 10 scfm). The second conventional test had an increase in the discharge rate of approximately 50 scfm. The stack flow was not measured during the 48-hour tests. The analytical summary for the contaminant concentration in the off-gas is presented in Table 5-8. During the 48-hour tests, the average TPH concentrations in the off-gas during the first conventional, knockout tank, dual drop tube, second conventional configurations were 4,900, 7,400, 2,800, and 3,500 ppmv, respectively. The one-week test had average TPH concentrations of 3,200, 520, 1,900, and 1,550 ppmv for the first conventional, knockout tank, dual drop tube, and second conventional configurations, respectively.

Table 5-8. Off-Gas Analytical Summary at NAS Fallon, NV

Test Configuration	TPH (C5+) (ppmv)	TPH (C2-C4) (ppmv)	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)
48 Hour Test						
1st Conventional	4,900	ND	53	20	17	48 (M)
Knockout Tank	7,400	ND	87	53	42	130 (M)
Dual Drop tube	2,800	18	31	13	11	29 (M)
2nd Conventional	3,500	ND	38	30	26	75 (M)
1 Week Test						
1st Conventional	3,200	ND	36	31	28	80 (M)
Knockout Tank	520	ND	5.7	6.2	5.2	15 (M)
Dual Drop tube	1,900	ND	15 (M)	15	14	42 (M)
2nd Conventional	1,550	ND	11 (M)	16	16	49 (M)

M = Reported value may be biased due to apparent matrix interferences.

5.1.1.3 Performance Data from Bolling AFB, Washington, DC

Table 5-9 details the operational data at Bolling AFB, Washington, DC. The demonstration was performed on well SL-1. During the course of the demonstration, approximately 35 gallons of LNAPL was extracted from the subsurface. Of this, approximately 16 gallons of clean LNAPL were recovered from the subsurface. Both the clean fuel and fuel from the floating solids were used in an attempt to accurately quantify the total amount of fuel recovered.

Table 5-9. Operational Data at Bolling AFB, Washington, DC

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Clean Fuel Recovered (gal)	Solids Recovered (gal)	Fuel and Fuel from Solids Recovered (gal)
1st Conventional	71.9	5,162.5	2.56	12.42	8.27
Knockout Tank	71.1	3,914.4	0.25	14.56	6.95
Dual Drop tube	71.7	4,562.1	8.83	5.35	11.29
2nd Conventional	70.5	4,530.2	4.26	8.50	8.17
Cumulative Operation	285.2	18,169.3	15.9	40.83	34.68

Floating solids samples were taken during each configuration and centrifuged down to determine the ratio of air, water and solids and product in the floating solids. Table 5-10 presents the average results of the centrifuge test. The first conventional and second conventional configurations had similar results. The knockout tank and the dual drop tube sample had a higher percent volume of solids. The sample collected during the dual drop tube test also contained no water and had a little over half the floating solids as fuel. Two samples of the floating solids were taken and were analyzed for suspended solids, calcium, magnesium, aluminum, iron, and oil and grease. The results are presented in Table 5-11. These samples were taken during the first conventional and the knockout tank configurations.

Table 5-10. Averaged Centrifuge Results at Bolling AFB, Washington, DC

Configuration	Water	Sediment	Fuel
	Percent by Volume		
1st Conventional	31	22	46
Knockout Tank	23	43	35
Dual Drop tube	0	46	54
2nd Conventional	34	20	46

Table 5-11. Solids Analytical Results at Bolling AFB, Washington, DC

Sample ID	Suspended Solids (mg/L)	Ca	Mg	Al	Iron	Oil & Grease (g/L)
		(mg/kg)				
Bolling-FS-2	2,840	140	ND	100	10,000	740
Bolling-FS-5	11,020	200	ND	240	29,000	410

During the tests in the conventional configuration, all of the fuel and floating solids were recovered in the standard oil/water separator. Of the LNAPL recovered, approximately 31% was recovered as clean fuel. When the knockout tank configuration was tested, approximately 4% of the LNAPL recovered was in the form of clean fuel. The knockout tank had the highest solids recovery. The dual drop tube configuration recovered the most amount of LNAPL with approximately 78% recovered as clean fuel. The second conventional configuration test had approximately 8 gallons recovered with 52% LNAPL recovered as clean fuel.

The groundwater recovery rate during each test and throughout the demonstration was relatively constant. The average groundwater recovery rate through the demonstration was approximately 1 gpm, and a total of 18,000 gallons of water was recovered during the demonstration.

Table 5-12 displays the analytical results of the water samples collected at the seal-tank water (before oil/water separation) and the process water (after the OWS) in each of the configurations

tested and the analytical results from the off-gas samples. The average TPH-E concentrations in the process water were 117, 87, 1.3, and 130 mg/L for the first conventional, knockout tank, dual drop tube, and second conventional configuration tests, respectively. The average TPH-E concentrations in the seal-tank water during the first conventional, knockout tank, dual drop tube, and second conventional test were 630, 677, 2.1, and 547 mg/L, respectively.

Table 5-12. Analytical Summary at Bolling AFB, Washington, DC

Test Configuration	Avg. TPH-E As Jet Fuel (mg/L)	Off-gas Avg. TPH (ppmv)
1st Conventional		
- Seal Tank Water	630	120
- Process Water	117	
Knockout Tank		
- Seal Tank Water	677	138
- Process Water	87	
Dual Drop tube		
- Seal Tank Water	2.1	100
- Process Water	1.3	
2nd Conventional		
- Seal Tank Water	547	180
- Process Water	130	

The stack gas discharge rate was nearly the same for the first conventional, knockout tank, dual drop tube, and second conventional configurations. The discharge rate was approximately 19 scfm. The average TPH concentrations in the off-gas during the first conventional, knockout tank, dual drop tube, and second conventional tests were 120, 138, 100, and 180 ppmv, respectively.

A baildown test was conducted at Bolling AFB to provide a qualitative indication of the presence of mobile, free-phase LNAPL and its recovery potential. The baildown test was conducted at well SL-2 (see Figure 3-5). The baildown test was performed using a peristaltic pump, which was used to skim fuel for 24 hours. The well was then monitored for fuel recovery every five minutes for the first 30 minutes, followed by hourly monitoring. The baildown test indicated a relatively slow rate of LNAPL recovery into the well and resulted in no appreciable LNAPL recovery within the first 24 hours. The well was monitored for an additional 72 hours with little fuel recovery. These data indicate that the LNAPL present at the site has a low mobility under passive conditions and therefore was relatively difficult to recover.

5.1.1.4 Performance Data from NAWC China Lake, California

Table 5-13 presents the operational data for NAWC China Lake, California. The demonstration was performed on well EW-2. The fuel recovery rates were relatively constant throughout each test of the demonstration, but they decreased over the total period. The LNAPL recovery rate ranged from approximately 31 to 46 gpd. The total amount of fuel recovered was approximately 577 gallons with 558 gallons recovered as clean fuel. The fuel recovery rates during the

knockout tank, first dual drop tube, second dual drop tube and second conventional test were similar and less than the fuel recovery rate during the first conventional test.

Table 5-13. Operational Data at NAWC China Lake, CA

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Clean Fuel Recovered (gal)	Solids Recovered (gal)	Clean Fuel and Fuel from Solids Recovered (gal)
1st Conventional	73.4	12,848.3	142.6	2.82	144.8
Knockout Tank	72.3	6,524.9	115.5	1.45	116.6
Dual Drop tube	73.1	6,824.5	94.5	11.70	103.5
2nd Dual Drop tube	72.9	7,031.8	106.3	0.0	106.3
2nd Conventional	74.7	5,074.2	99.4	8.46	105.9
Cumulative Bioslurper Operation	366.4	38,303.7	558.3	24.43	577.1

The groundwater recovery rate during the knockout tank, first dual drop tube, second dual drop tube and the second conventional configuration were relatively constant with an average rate of approximately 1.5 gpm. During the first conventional configuration test, the water meter stopped working at the 12-hour mark after initiating the test, so another meter was put in line. An approximate water recovery amount was based on the level of water within the water storage tank. The approximate water recovery rate was estimated at 3 gpm for the first conventional configuration test. The drop tube was placed at the static oil/water interface, which elevated after the initial slug of LNAPL was removed causing a higher water recovery for this conventional configuration test. A total of approximately 38,000 gallons was recovered during the demonstration with approximately 13,000 gallons being recovered during the first conventional test and an average of 6,500 gallons per test being recovered during the knockout tank, first dual drop tube, second dual drop tube and second conventional tests.

Table 5-14 presents the analytical results of the floating solids sample that was taken during the knockout tank configuration. A centrifuge test was performed on floating solids samples that were taken from each configuration. The first conventional, knockout tank, and second conventional configurations had similar percent by volume of sediment, water and fuel of 19, 4, and 77%, respectively. The first dual drop tube floating solids sample consists primarily of water at 52% by volume, 43% fuel by volume, and 5% sediment. The second dual drop tube did not produce floating solids.

Table 5-14. Solids Analytical Results at NAWC China Lake, CA

Sample ID	Sample Composition by % Weight			Moisture of Solid Phase	Suspended Solids	Ca	Mg	Al	Iron	Oil & Grease
	Oil	Water	Solid	%	(mg/L)	(mg/kg)				(g/L)
China Lake-FS-3	77.4	20.1	2.6	67.7	1,300	5,700	1,000	680	32,000	608

Table 5-15 displays the analytical results of the water samples collected at the seal water tank the process water in each of the configurations tested, and the analytical results from the off-gas samples. During the first conventional bioslurper test, the average TPH-E concentrations in the process water and seal-tank water were 300 and 4,400 mg/L, respectively. The average TPH-E concentrations in the process water and seal-tank water during the knockout tank configuration were 550 and 2,333 mg/L, respectively. For the first dual drop tube configuration, the TPH-E concentrations had approximately the same average concentrations as the knockout tank test for the process water and seal-tank water, which were 562 and 2,200 mg/L, respectively. The second dual drop tube configuration, the TPH-E concentrations in both the process water and seal-tank water, decreased with average concentrations of 7.2 mg/L for both the process water and seal-tank water. During the second conventional bioslurper test, the average TPH-E concentrations in the process water and seal-tank water were 673 and 3,300 mg/L, respectively.

Table 5-15. Analytical Summary at NAWC China Lake, CA

Test Configuration	Avg. TPH-E As Jet Fuel (mg/L)	Avg. TPH-P (mg/L)	Off-Gas Avg. TPH (ppmv)
1st Conventional			
- Seal Tank Water	4,400	28	2,450
- Process Water	300	11	
Knockout Tank			
- Seal Tank Water	2,333	29	2,950
- Process Water	550	15	
Dual Drop tube			
- Seal Tank Water	2,200	12	3,350
- Process Water	562	9.6	
2nd Dual Drop tube			
- Seal Tank Water	7.2	3.8	2,250
- Process Water	7.2	3.9	
2nd Conventional			
- Seal Tank Water	3,300	39	3,225
- Process Water	673	19	

The first conventional, knockout tank, second dual drop tube, and second conventional had similar stack gas discharge rates during operation. The discharge rate was approximately 18 scfm. The first dual drop tube had a higher stack gas discharge rate of approximately 40 scfm. The average TPH concentration in the off-gas during the first conventional, knockout tank, first dual drop tube, second dual drop tube, and second conventional test were 2,450, 2,950, 3,350, 2,250, and 3,225 ppmv, respectively.

A baildown test conducted at NAWC China Lake provided a qualitative indication of the presence of mobile, free-phase LNAPL and its recovery potential. The baildown test was conducted at well EW-2. In the first five minutes after bailing was completed, the well recovered 25% of the original LNAPL thickness. Another 25% of the LNAPL thickness was recovered within the next 24 hours.

5.1.1.5 Performance Data from Tyndall AFB, Florida

Table 5-16 presents the operational data for the demonstration at Tyndall AFB, Florida. The demonstration was performed on well 1220. The fuel recovery rates show a decrease in fuel recovery after eight hours of the first conventional configuration test. The dual drop tube configuration, which was performed next showed a relatively constant fuel recovery rate. The knockout tank and the second conventional configuration recovered little fuel during the tests. During the course of the demonstration, approximately 15 gallons of LNAPL were recovered from the subsurface. Of this, approximately 11 gallons of clean LNAPL were recovered from the subsurface. Both the clean fuel and the fuel from the floating solids were used in an attempt to accurately quantify the total amount of fuel recovered.

Table 5-16. Operational Data at Tyndall AFB, FL

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Fuel Recovered (gal)	Solids Recovered (gal)	Fuel and Fuel from Solids Recovered (gal)
1st Conventional	49.6	2,940.7	1.07	6.85	4.02
Knockout Tank	48.8	2,781.6	0.14	0.89	0.52
Dual Drop tube	48.4	2,940.7	9.94	0.0	9.94
2nd Conventional	48.4	2,747.2	0.0	1.10	0.47
Cumulative Bioslurper Operation	195.2	13,208.2	11.14	8.84	14.94

Floating solids samples were taken during each configuration and centrifuged to determine the percent by volume of water, sediment, and fuel in the sample. Table 5-17 presents the averaged centrifuge results for each configuration where floating solids samples could be taken. Samples of the floating solids were also sent to an analytical laboratory for particulate analysis. The results are presented in Table 5-18. Tyndall-FS-1 was taken during the first conventional, while Tyndall-FS-3 was taken during the knockout tank configuration test.

Table 5-17. Averaged Centrifuge Results at Tyndall AFB, FL

Configuration	Water	Sediment	Fuel
	Percent by volume		
1st Conventional	48	8	44
Knockout Tank	28	23	49
2nd Conventional	64	9	27

Table 5-18. Floating Solids Analytical Results at Tyndall AFB, FL

Sample ID	Sample Composition by % Weight			Moisture of Solid Phase	Suspended Solids	Ca	Mg	Al	Iron	Oil & Grease
	Oil	Water	Solid	%	(mg/L)	(mg/kg)				(g/L)
Tyndall-FS-1	35.7	60.7	3.6	88	1,957	480	120	3,200	17,000	250
Tyndall-FS-3	73	24.4	2.6	95	500	430	100	2,900	16,000	281

The groundwater recovery rate during each test and throughout the demonstration was relatively constant. The average groundwater recovery rate through the demonstration was approximately 1 gpm, and a total of 13,000 gallons of water were recovered during the demonstration.

Table 5-19 presents the analytical results of the water samples collected at the seal water tank (before oil/water separation) and the process water (after the OWS) in each of the configurations tested. During the first conventional bioslurper test, the average TPH-E concentrations in the process water and seal-tank water were 158 and 278 mg/L, respectively. The average TPH-E concentrations in the process water and seal-tank water during the knockout tank configuration were 425 and 1,150 mg/L, respectively. In the dual drop tube configuration, TPH-E in both the process water and seal-tank water was not detected. During the second conventional bioslurper test, the average TPH-E concentrations in the process water and seal-tank water were 300 and 820 mg/L, respectively.

Table 5-19. Process Water and Seal-Tank Water Analytical Summary at Tyndall AFB, FL

Test Configuration		Avg. TPH-E As Jet Fuel (mg/L)	Avg. TPH-E As Diesel (mg/L)	Avg. TPH- P (mg/L)
1st Conventional	- Seal Tank Water	278	ND	28
	- Process Water	158	ND	34
Knockout Tank	- Seal Tank Water	1,150	ND	32
	- Process Water	425	ND	16
Dual Drop tube	- Seal Tank Water	ND	0.47	4.7
	- Process Water	ND	0.16	5.1
2nd Conventional	- Seal Tank Water	820	ND	57
	- Process Water	300	ND	80

ND = Not detected

The stack gas discharge rates were nearly the same when the first conventional, knockout tank, dual drop tube, and second conventional were being operated. The discharge rate was approximately 20 scfm. Table 5-20 presents the analytical results of the off-gas samples in each test configuration. The average TPH concentration in the off-gas during the first conventional, knockout tank, dual drop tube, and second conventional test were 6,533, 5,200, 4,000, and 3,800 ppmv, respectively.

Table 5-20. Off-Gas Analytical Results at Tyndall AFB, FL

Test Configuration	TPH (C5+) (ppmv)	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)
1st Conventional	6,533	423	69	16	74
Knockout Tank	5,200	265	90	26	111
Dual Drop tube	4,000	200	36	17	92
2nd Conventional	3,800	190	66	20	80

5.1.1.6 Performance Data from NFD Point Molate, California

Table 5-21 presents the operational data for NFD Point Molate, California. The limited LNAPL recovery rate at MW11-27R necessitated the reconfiguration of the system to operate at P86-13/14. During the operation at P86-13/14, the LNAPL-recovery rates were relatively low during the first 24 hours of the test in the conventional configuration (1 gallon was recovered). Throughout the remainder of the demonstration, the recovery rates were very low (< 0.3 gal/day). However, the LNAPL recovery rates during the dual drop tube test were on average higher than when the conventional configuration was being tested. Following the demonstration at P86 13/14, a 24-hour test was conducted at MW11-36 to determine the feasibility of using the dual drop tube system with higher viscosity fuels (Bunker Fuel). During the entire demonstration (including operation at MW11-27R and MW11-36), approximately 9 gallons of LNAPL were extracted from the subsurface. These data include approximately 6 gallons of LNAPL that were removed from well P86-13/14 during the baildown test prior to initiating the extraction testing at that well.

Table 5-21. Operational Data at NFD Point Molate, CA

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Fuel Recovered (gal)
Conventional Test at MW11-27R	59.0	9,915.0	0.0
1st Conventional Test (P86 13/14)	72.3	8,466.0	1.08
Dual Drop tube Test (P86 13/14)	72.9	3,977.5	0.37
2nd Conventional Test (P86 13/14)	36.4	2,425.9	0
Dual Drop tube Test (MW11-36)	24.3	1,147.1	1.35
Cumulative Bioslurper Operation	264.9	25,931.5	2.8

The groundwater-recovery rates were varied depending on the well that was connected to the bioslurper. During operation at MW11-27R, the groundwater recovery rates were between 2.5 and 3.5 gallons per minute (gpm). Very low groundwater recovery rates (0.10 gpm) were recorded when the system was initially installed on P86-13/14. Recovery rates of less than 0.5 gpm can result in the liquid ring pump overheating and shutting down. To prevent shutdown of the system, tap water was metered into the seal water reservoir. For the first 24 hours of the test in the conventional configuration, the tap water was introduced at a rate of approximately 3 gpm. This flowrate was considered excessive, so the flowrate was reduced to approximately 1.5 gpm for the remainder of the first conventional test. The tap water was metered into the system at about 1 gpm for the dual drop tube and the second conventional configuration. The groundwater recovery rate during the operation at MW11-36 also was about 1 gpm.

Table 5-22 displays analytical results from process water and seal-tank water samples that were collected during the demonstration. The concentrations of TPH in the groundwater at MW11-27R and MW11-36 were measured at 2.5 and 1.2 mg/L, respectively. At well MW11-27R, only the conventional system was tested because no LNAPL was recovered. The average TPH concentrations at MW11-27R for the conventional test for the seal-tank water and the process water was 3.0 and 1.6 mg/L, respectively. The average TPH concentration in the seal-tank water

and process water during the first conventional test at P86-13/14 was 27.7 and 21.0 mg/L, respectively. The average TPH concentration in the seal-tank water and process water during the dual drop tube test was 2.6 and 0.74 mg/L, respectively. During the second conventional test, the average TPH concentration in the seal-tank water and process water was 3.6 and 3.0 mg/L, respectively. A dual drop tube test was performed on well MW-36 and samples were taken. The average TPH concentration of the seal-tank water and the process water for the dual drop tube test was 0.92 and 0.84 mg/L, respectively.

Table 5-22. Process Water and Seal-Tank Water Analytical Summary at NFD Point Molate, CA

Test Configuration		Avg. TPH-E As Diesel (mg/L)	Avg. TPH-E As Oil (mg/L)
1st Conventional at Well MW11-27R	- Seal Tank Water	3.0	ND
	- Process Water	1.6	ND
1st Conventional at Well P86-13/14	- Seal Tank Water	27.7	1.7
	- Process Water	21.0	1.1
Dual Drop tube at Well P86-13/14	- Seal Tank Water	2.6	0.18
	- Process Water	0.74	ND
2nd Conventional at Well P86-13/14	- Seal Tank Water	3.6	0.6
	- Process Water	3.0	0.6
Dual Drop tube Fuel at Well MW11-36	- Seal Tank Water	0.92	ND
	- Process Water	0.84	ND

Table 5-23 presents the results obtained from the LNAPL sample analyses. Two samples of LNAPL were collected, one from P86-13/14 and the other from MW11-36. The LNAPL sample was analyzed for viscosity only. The analytical results indicate that the viscosity of the samples from P86-13/14 and MW11-36 were 1.9 and 4.7 centistokes (cSt).

Table 5-23. Viscosity Analytical Results at NFD Point Molate

Sample ID	Viscosity (cSt) at 100°C
Molate-P86-13/14-FP (diesel)	1.9
Molate-MW11-36-FP (bunker fuel)	4.7

The stack gas discharge rate (which equals the soil gas extraction rate) was dependent on the well that was used. The off-gas discharge rate during operation at well MW11-27R averaged 5 scfm. During operation at P86-13/14 the average discharge rate was approximately 35 scfm. The flowrates were nearly the same when the standard and dual drop tube configurations were being operated. The discharge rate when operating at MW11-36 was approximately 28 scfm.

Off-gas TPH concentration samples were taken during the tests at P86-13/14 and the dual drop tube test at the bunker fuel site (well MW11-36). The average TPH concentrations in the off-gas for well P86-13/14 in the conventional, dual drop tube and second conventional are 131, 100, and 90 ppmv, respectively. Table 5-24 presents the analytical results from the off-gas samples that were collected during the demonstration. The average TPH concentration for the dual drop tube test for well MW11-36 is 46 ppmv.

Table 5-24. Off-Gas Analytical Summary at NFD Point Molate, CA

Test Configuration	TPH (C2-C4) (ppmv)	TPH (C5+) (ppmv)	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)
1st Conventional (P86-13/14)	ND	131	2.2	0.23	0.57	2.5
Dual Drop Tube (P86-13/14)	ND	100	1.5	0.11	0.3	1.3
2nd Conventional (P86-13/14)	ND	90	1.3	0.12	0.27	1.3
Dual Drop Tube (MW11-36)	ND	46	0.11	0.11	0.26	1.1

The vacuum levels in the vadose zone were monitored at the soil gas monitoring points and well MW11-26 during the first test in the standard configuration. After initiating the bioslurper system, the vacuum levels in the vadose zone reached equilibrium levels after approximately 24 hours. The average equilibrium vacuum levels were 17, 0.035, 0.018, and 0.015, at distances from well MW11-27 of 0, 10, 20 and 40 ft, respectively. The vadose zone radius of influence was calculated by plotting the log of the average vacuum level at the monitoring points versus the distance from the extraction well. The radius of influence then was defined as the distance from the extraction well where 0.1 inch of H_2O can be measured. Based on this definition, the radius of influence during the bioslurper pump test at MW11-27R was approximately 8 ft.

5.1.1.7 Performance Data from MCAS Cherry Point, North Carolina

Table 5-25 presents summary data gathered during the operation in the different configurations. The demonstration was performed on well MW-02. LNAPL was only recovered in the dual drop tube configuration at a relatively low rate of 0.3 gallons per day. It is likely that LNAPL was being removed from the well during operation in the standard configuration; however, because the LNAPL is incidentally mixed with the groundwater during extraction in the standard configuration, the LNAPL passes through the system in an emulsified form and the volume cannot be measured. Floating solids were not seen in either configuration.

The groundwater recovery was consistent throughout the tests. The average groundwater recovery was 4.5 gpm. Approximately 31,000 gallons of groundwater were recovered during the demonstration.

Table 5-25. Operational Data at Site 1640 MCAS Cherry Point, NC

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Total Fuel Recovered (gal)
1st Conventional Test	31.2	8,499	0
Dual Drop tube Test	47.4	12,384	0.7
2nd Conventional Test	35.9	9,910	0
Cumulative Bioslurper Operation	114.5	30,793	0.7

Table 5-26 presents the analytical summary for the process water, seal-tank water and the off-gas. During operation in the conventional configuration, the average TPH concentrations in the seal water (in the liquid ring pump system) and process water (effluent from the oil/water separator) were 28 and 30 mg/L, respectively. During the operation with the dual drop tube system, the seal water and process water concentrations were reduced to 1.4 and 0.4 mg/L (average), respectively.

Table 5-26. Analytical Summary at MCAS Cherry Point, NC

Test Configuration		Avg. TPH-E As Diesel (mg/L)	Off-Gas Avg. TPH (ppmv)
1st Conventional	- Seal Tank Water	24	1,560
	- Process Water	33	
Dual Drop tube	- Seal Tank Water	1.45	314
	- Process Water	0.48	
2nd Conventional	- Seal Tank Water	32	237
	- Process Water	27	

The stack gas discharge rates were nearly the same when the first conventional, dual drop tube, and second conventional were being operated. The discharge rate was approximately 5 scfm. A handheld meter measured off-gas from the stack. These measurements were taken at baseline every two hours for the first 24 hours and then every 12 hours after that until the end of the test for each configuration. These measurements were average for each configuration. The average TPH for the first conventional, dual drop tube, and second conventional configurations are 1,560, 314, and 237 ppmv, respectively.

5.1.1.8 Performance Data from Hickam AFB, Hawaii

Table 5-27 presents the operational data for Hickam AFB, Hawaii. The demonstration was performed on well S511-EW02. The fuel recovery rates were relatively constant through the first conventional test and the dual drop tube test. The second conventional test shows a decrease in LNAPL recovery. The dual drop tube configuration test shows a slight increase in LNAPL recovery compared to the first conventional test. In the first conventional test approximately 114 gallons of LNAPL was extracted from the subsurface. The dual drop tube

configuration test extracted approximately 140 gallons from the subsurface. The second conventional test only recovered approximately 35 gallons. A total of approximately 288 gallons was extracted from the subsurface. Floating solids were not produced in significant quantities in any of the configurations, but the dual drop tube configuration appeared to reduce the production of the by-products.

Groundwater recovery rates were very low for all three tests. The dual drop tube test and the second conventional test recovered groundwater at a rate of 0.1 gpm. The first conventional test had approximately the same groundwater recovery until about 16 hours after the start of the test when the water meter was thought to be clogged. The water meter was replaced at 50 hours and the same general slope of groundwater recovery can be seen in the graph of groundwater recovery.

Table 5-27. Operational Data at Hickam AFB, HI

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Fuel Recovered (gal)
1st Conventional Test	72.9	255.1	114
Dual Drop tube Test	67.9	428.8	139.4
2nd Conventional Test	72.0	500.2	35
Cumulative Bioslurper Operation	212.8	1184.1	288.4

Table 5-28 displays the analytical summary from the process water and seal-tank water samples that were collected during the demonstration. The concentration of TPH in the groundwater was measured at 44 mg/L. During the first conventional configuration test, the average TPH-E concentrations in the process water (after the OWS) and the seal-tank water (before the OWS) were 59 and 1,717 mg/L, respectively. The average TPH-E concentrations in the process water and seal-tank water during the dual drop tube configuration were 26 and 102 mg/L, respectively. During the second conventional configuration test, the average TPH-E concentrations in the process water and seal-tank water were 36 and 1,327 mg/L, respectively.

Table 5-28. Process Water and Seal-Tank Water Analytical Summary at Hickam AFB, HI

Test Configuration		Avg. TPH-E (Jet Fuel) (mg/L)	Avg. TPH-E (Oil) (mg/L)
1st Conventional	- Seal Tank Water	1,717	ND
	- Process Water	59	2.8
Dual Drop tube	- Seal Tank Water	102	1.5
	- Process Water	26	ND
2nd Conventional	- Seal Tank Water	1,327	ND
	- Process Water	36	ND

Table 5-29 displays the analytical results from off-gas samples that were collected during the demonstration. The average TPH concentration in the off-gas during the first conventional, dual drop tube, and the second conventional tests were 31,333, 24,333 and 26,333 ppmv, respectively. These measured concentrations could be slightly lower than actual concentrations because of problems associated with system shutdown and the bleeding of ambient air into the system. The stack gas discharge rate (which equals the soil gas extraction rate) remained consistent throughout the demonstration at an average rate of 35 scfm.

Table 5-29. Off-Gas Analytical Results at Hickam AFB, HI

Test Configuration	TPH (C5+) (ppmv)	Benzene (ppmv)	Toluene (ppmv)	Ethylbenzene (ppmv)	Total Xylenes (ppmv)
1st Conventional	31,333	1,167	230	117	287
Dual Drop tube	24,333	900	233	170	447
2nd Conventional	26,333	933	260	180	550

The vacuum levels in the vadose zone were monitored at the soil-gas monitoring points throughout the duration of the demonstration. After initiating the bioslurper system, the vacuum levels in the vadose zone reached equilibrium levels after approximately 24 hours. The average equilibrium vacuum levels were 0.57, 0.53, and 0.38 and distances from the well were approximately 20, 32, and 50 ft, respectively. The vadose zone radius of influence was calculated by plotting the log of the average vacuum level at the monitoring points versus the distance from the extraction well. The radius of influence then was defined as the distance from the extraction well where 0.1 inch of H_2O can be measured. Based on this definition, the vadose zone radius of influence during the bioslurper pump test was approximately 95.6 ft.

5.1.2 Performance Data for the Long-Term Demonstration Site

The operational data for the long-term demonstration at NAS Fallon, Nevada, is presented in Table 5-30. The total amount of fuel recovered from the subsurface for the four months of the long-term demonstration is approximately 6,845 gallons. The first conventional configuration had the greatest recovery with approximately 155 gpd with a total of approximately 1,062 gallons of LNAPL over 164 hours. The next three tests used the dual drop tube configuration without the surge tank and gradually added on new wells over a period of 5 days. For the single well dual drop tube, an approximate 73 gallons were recovered with an average 39 gpd LNAPL recovery over 44 hours. The two well dual drop tubes and all five wells recovered approximately 63 and 641 gallons, respectively, with an average LNAPL recovery of 29 and 80 gpd, respectively. The two well dual drop tubes lasted 57 hours while the five dual drop tubes lasted approximately 192 hours. The next configuration that was tested was the five well dual drop tubes with the use of a surge tank. This was run for approximately 1,183 hours and recovered 3,434 gallons of LNAPL with an average LNAPL recovery of 70 gpd. The knockout tank was tested after this and recovered 894 gallons over 333 hours with an average LNAPL recovery of 64 gpd. The last configuration tested was the second conventional which lasted approximately 161 hours and recovered 516 gallons of LNAPL with a recovery of 77 gpd.

The total groundwater recovery for the long-term demonstration is approximately 252,700 gallons. The average groundwater recovery was approximately 1.9 gpm over the length of the demonstration ranging from 1.2 during the second conventional to 2.9 during the single well dual drop tube test without the surge tank.

Floating solids were not formed in any recoverable amounts in any configuration during the demonstration.

Table 5-30. Operational Data for Long-Term Demonstration at NAS Fallon, NV

Test Configuration	Test Duration (hrs)	Water Recovered (gal)	Fuel Recovered (gal)
1st Conventional	164.2	19,463.9	1,062.0
Single Well Dual Drop tube w/o Surge Tank	44.4	8,075.7	72.6
Two Wells Dual Drop tube w/o Surge Tank	57.4	5,127.8	63.0
Five Wells Dual Drop tube w/o Surge Tank	191.7	24,651.6	640.5
Five Wells Dual Drop tube w/ Surge Tank	1,183.2	139,844.9	3,433.6
Knockout Tank	332.7	28,312.1	893.6
2nd Conventional	160.8	11,720.2	515.5
Cumulative Bioslurper Operation	2,134.4	252,705.3	6,844.8

Table 5-31 displays the analytical summary from the process water and seal-tank water samples that were collected during the demonstration. The concentration of TPH in the groundwater was measured at 0.59 mg/L. The average seal-tank water TPH concentration in the first conventional, single well dual drop tube, two well dual drop tube, five well dual drop tube, five dual drop tubes with surge tank, knockout tank, and second conventional are 10,067, 15, 63, 180, 109, 855, and 4,800 mg/L, respectively. The average process water TPH concentration in the first conventional, single well dual drop tube, two well dual drop tube, five well dual drop tube, five well dual drop tube with surge tank, knockout tank, and second conventional are 780, 1.9, 26, 78.5, 33, 290, and 390 mg/L, respectively.

The stack gas discharge rate was not dependent on the number of wells that were being used. The average discharge rate was approximately 35 scfm for the different configurations. Table 5-31 presents the off-gas analytical summary. The average off-gas TPH concentrations for the first conventional, single well dual drop tube, five well dual drop tube, five well dual drop tube with surge tank, knockout tank, and second conventional are 780, 1,900, 2,000, 704, 620, and 520 ppmv, respectively.

5.2 Data Assessment

The assessment of the eight short-term demonstration sites and the long-term demonstration site was based primarily on the aqueous and vapor TPH concentrations. A secondary assessment was done on the production (volume and appearance) of floating solids and emulsions formed by the different configurations. Data was also taken on the different configurations, recovery of the LNAPL and groundwater.

Table 5-31. Process Water, Seal-Tank Water, and Off-Gas Analytical Summary for the Long-Term Demonstration ay NAS Fallon, NV

Test Configuration		Avg. TPH-E (Jet Fuel) (mg/L)	Avg. TPH (C2+ ref. JP-4) (ppmv)
1st Conventional	- Seal Tank Water	10,067	780
	- Process Water	780	
Single Well Dual Drop tube w/o Surge Tank	- Seal Tank Water	15	1,900
	- Process Water	1.9	
Two Wells Dual Drop tube w/o Surge Tank	- Seal Tank Water	63	NS
	- Process Water	26	
Five Wells Dual Drop tube w/o Surge Tank	- Seal Tank Water	180	2,000
	- Process Water	78.5	
Five Wells Dual Drop tube w/ Surge Tank	- Seal Tank Water	109	704
	- Process Water	33	
Knockout Tank	- Seal Tank Water	855	620
	- Process Water	290	
2nd Conventional	- Seal Tank Water	4,800	520
	- Process Water	390	

NS = Not sampled

5.2.1 Data Assessment of the Short-Term Demonstration Sites

This section details the data assessment for the eight short-term demonstration sites. Figures 5-4 and 5-5 compare the dual drop tube configuration with the conventional configuration for both the seal tank effluent water and the off-gas average analytical results, respectively. Figures 5-6 and 5-7 show the comparison of the knockout tank and the conventional configuration of the seal water tank and off-gas average analytical results, respectively.

5.2.1.1 Data Assessment at NCBC Davisville, Rhode Island

Several wells were used during the demonstration because of the limited LNAPL volume present at the site. In the second conventional, LNAPL was not recovered and the groundwater recovery was less than 0.1 gpm. Therefore, the first conventional, dual drop tube, and knockout tank data will be compared because LNAPL was recovered during these tests.

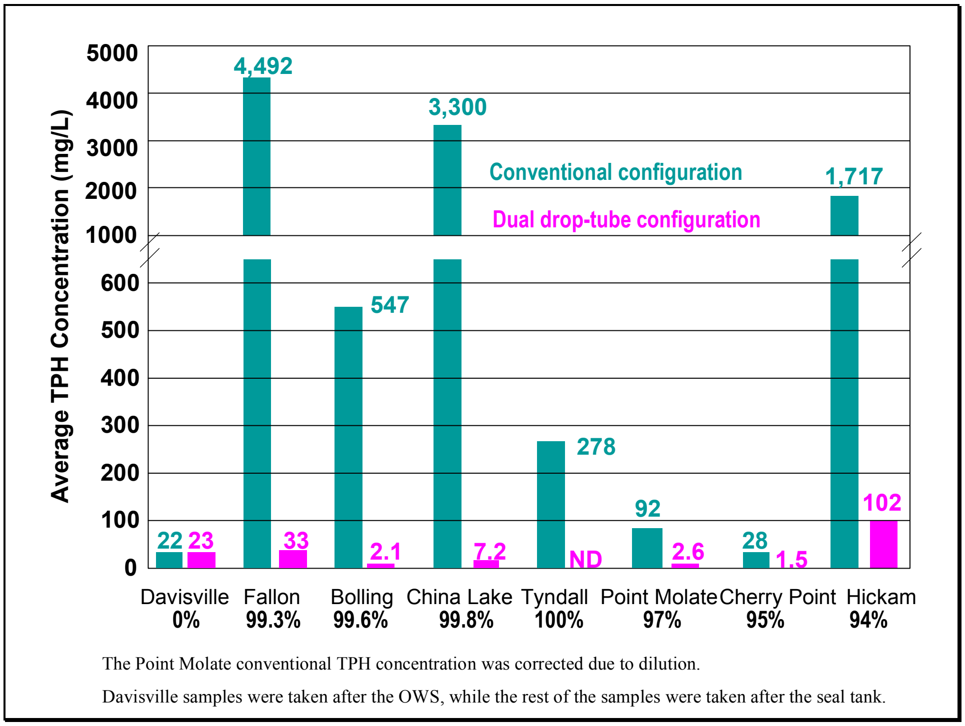


Figure 5-4. Comparison of Seal Tank Water Samples of the Dual Drop tube and the Conventional Configurations

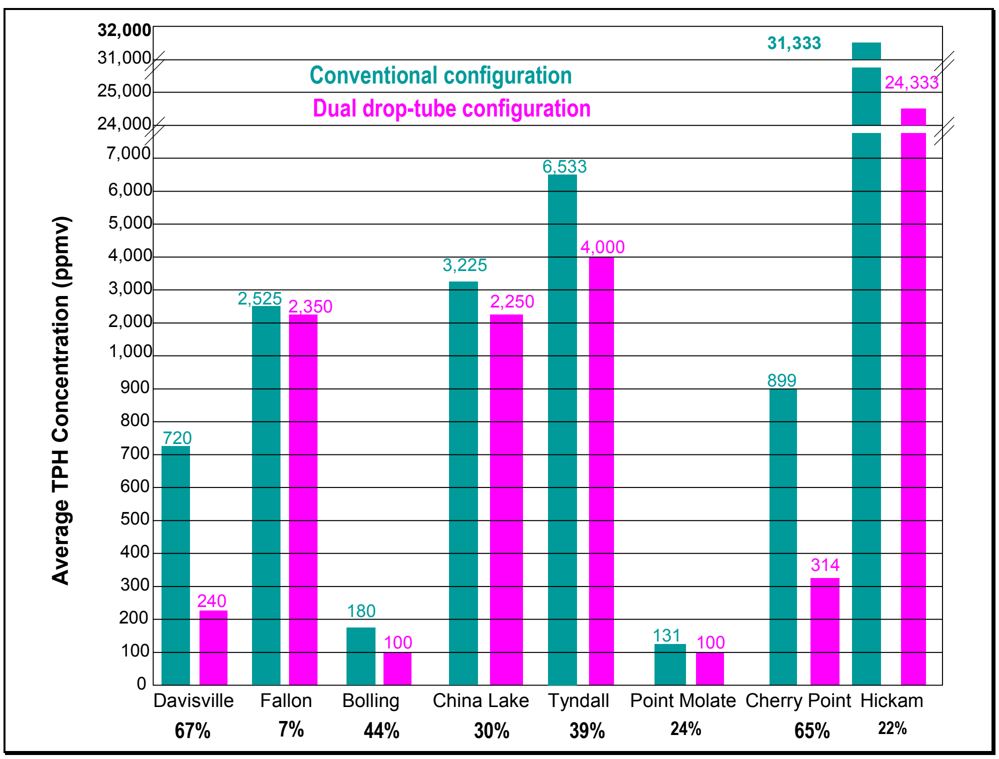
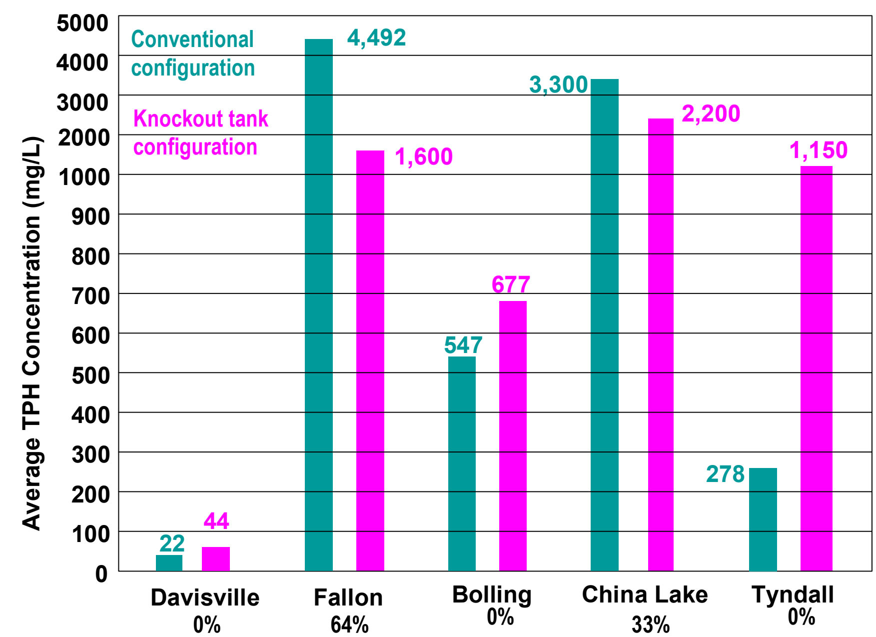


Figure 5-5. Comparison of Off-Gas Samples of the Dual Drop tube and the Conventional Configurations



Davisville samples were taken after the OWS, while the rest of the samples were taken after the seal tank.

Figure 5-6. Comparison of Seal Tank Water Samples of the Knockout Tank and the Conventional Configurations

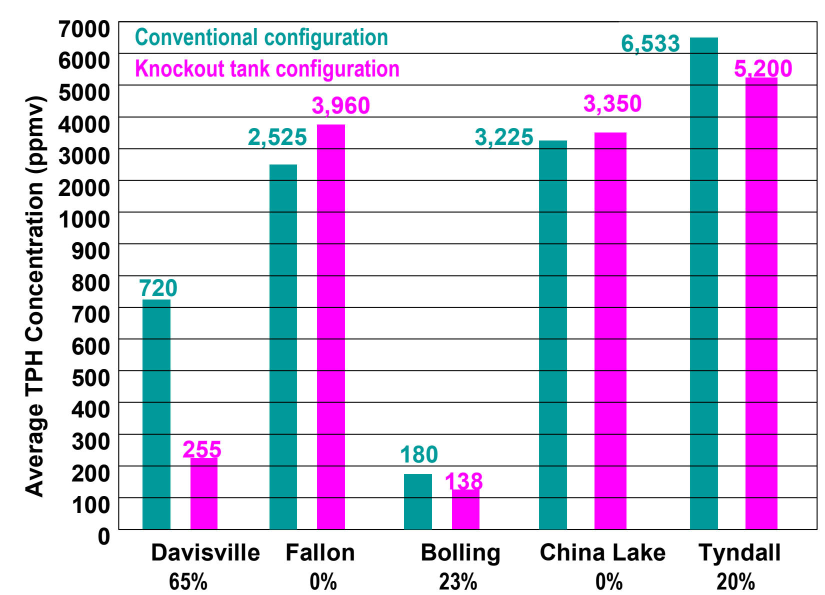


Figure 5-7. Comparison of Off-Gas Samples of the Knockout Tank and the Conventional Configurations

The TPH concentrations in the process water did not show a significant difference in concentration with any of the configurations that were tested during the demonstration. The insignificant changes in TPH concentrations were likely the result of 1) the low LNAPL and groundwater recovery rates and 2) the location for the process water sampling (i.e., after the OWS). The relatively low LNAPL recovery rates likely would have resulted in the limited degree of contamination in the seal tank water. Even if the LNAPL-recovery rates and the TPH concentrations in the seal water tank were high, the low water recovery rate (0.1 gpm) and the oversized OWS (30-gpm capacity) would cause significant oil/water separation and reduction in the process water TPH concentrations. It is believed that low groundwater recovery rate and the oversized OWS caused the TPH concentrations in the process water to be similar during all of the operations and concentrations.

In the knockout tank and the dual drop tube configurations, the petroleum hydrocarbon TPH concentrations were reduced in the bioslurper off-gas stream. The knockout tank separator resulted in a reduction of the TPH concentration of 65%, while the dual drop tube system resulted in a TPH reduction of 67% compared to the first conventional configuration.

The testing of the prepump separation systems at NCBC Davisville resulted in the reduced production of floating solids and frothy emulsion when the knockout tank and dual drop tube systems were used relative to the operation of the bioslurper system in the standard configuration. However, the limited amount of floating solids that were formed or captured in the knockout tank were difficult to remove and accurately quantify from the knockout tank because of the small (3/4 inch) discharge port for the fuel and floating solids that often became clogged.

5.2.1.2 Data Assessment at NAS Fallon, Nevada

Two separate tests were performed at NAS Fallon. One was a 48-hour test while the other was a one-week test for each configuration. Prepump separation technologies were performed during both tests. In both the 48-hour test and the one-week test, the fuel recovery rates during the knockout tank, dual drop tube and second conventional configurations were similar and less than the fuel recovery rate during the first conventional configuration. Due to the similarity of the LNAPL-recovery rate during the last three phases of both the 48-hour test and the one-week test, the data from these three configurations will primarily be used for comparison of the effectiveness of the prepump separation systems.

During the 48-hour test, the knockout tank configuration was effective at reducing the TPH concentrations in the seal-tank water by 64% relative to operation during the second conventional configuration. The one-week test had similar results with the knockout tank configuration reducing TPH concentration in the seal-tank water by 60% relative to the operation in the second conventional configuration. During both the 48-hour test and the one-week test, the dual drop tube configuration was effective at reducing the TPH concentration in the seal-tank water by 99% relative to operation during the second conventional configuration.

The TPH concentrations in the off-gas stream appeared to be unaffected by the use of the prepump separation systems. During the 48-hour tests, the average concentration of TPH in the off-gas was greater during the knockout tank configuration and nearly the same during the dual

drop tube configuration relative to off-gas data generated in the second conventional test. During the one-week tests, there were similar results except the dual drop tube configuration had elevated TPH concentrations compared to the second conventional configuration. The knockout tank configuration had a slight reduction in the TPH concentrations compared to the second conventional configuration.

Floating solids were not produced in significant quantities in any of the configurations during either the 48-hour test or the one-week test. The knockout tank and dual drop tube configurations appeared to reduce the production of the milky emulsions in the process water of both the 48-hour test and the one-week test.

5.2.1.3 Data Assessment at Bolling AFB, Washington, DC

The groundwater recovery was similar through all three configurations. The LNAPL recovery was approximately the same through the three configurations, taking into account the clean fuel recovered and the fuel extracted from the floating solids. The dual drop tube configuration had the highest clean LNAPL recovery. The knockout tank configuration had the highest percentage of floating solids with 96% of the LNAPL in one form of floating solids. The second conventional configuration had an even amount of clean fuel and fuel from floating solids recovered, with the first conventional having a higher portion of fuel from the floating solids. The effectiveness of the knockout tank and dual drop tube configuration was evaluated using data from the knockout tank, dual drop tube, and second conventional configurations due to the similar fuel and groundwater recovery during these tests.

The average extractable TPH concentrations measured during the knockout tank configuration test were not significantly different than those measured during the second conventional configuration test. The dual drop tube system significantly reduced the average extractable TPH concentration in the seal-tank water relative to the second conventional configuration. The extractable TPH in the seal-tank water was reduced approximately 99.6% in the dual drop tube configuration compared to the second conventional configuration.

The knockout tank configuration reduced the TPH concentrations in the off-gas. The TPH concentration reduction was 23% compared to the second conventional configuration. The dual drop tube configuration also appeared to reduce the concentration of petroleum hydrocarbons in the off-gas from the bioslurper. The TPH concentration was reduced 44% by using the dual drop tube configuration compared to the second conventional configuration.

The knockout tank configuration did not provide reasonable separation of the LNAPL and groundwater before the liquid ring pump and relatively large volumes of floating solids were produced in the extraction process. The knockout tank configuration only retained approximately 20% of the LNAPL and the remainder passed through to the liquid ring pump and then to the standard OWS. The dual drop tube configuration prevented the fuel from entering the liquid ring pump (i.e., all of the LNAPL was trapped in the liquid trap), and no floating solids were present in the standard OWS. Additionally, the dual drop tube nearly eliminated the production of floating solids in the postpump-treatment equipment.

5.2.1.4 Data Assessment at NAWC China Lake, California

Due to the similarity of the LNAPL-recovery rate during the knockout tank, second dual drop tube, and the second conventional configuration, the data from these three tests will primarily be used for comparison of the effectiveness of the prepump separation systems. The groundwater recovery rate was also similar between the knockout tank, second dual drop tube and second conventional configurations.

The knockout tank system was effective at reducing the extractable TPH concentrations in the seal-tank water by 33% relative to operation in the second conventional configuration. The second dual drop tube was effective at reducing the extractable TPH concentration in the seal-tank water by 99.8% relative to operation in the second conventional configuration.

The TPH concentrations in the off-gas appeared to be decreased by the use of the dual drop tube prepump separation systems, while the knockout tank configuration did not show a decrease in the TPH concentration in the off-gas. The dual drop tube showed a 30% decrease in TPH concentrations relative to operation in the second conventional configuration.

Floating solids production was decreased in the knockout tank by 83% relative to operation in the second conventional configuration. The dual drop tube eliminated the production of floating solids in the postpump-treatment equipment.

5.2.1.5 Data Assessment at Tyndall AFB, Florida

LNAPL recovery decreased over the course of the demonstration with only a half gallon recovered during the second conventional configuration test. Therefore, the data from the knockout tank, dual drop tube, and the first conventional configurations were used to evaluate the effectiveness of the prepump separation systems. The groundwater recovery remained constant during the demonstration.

The average extractable TPH concentrations were slightly higher in the knockout tank configuration than either the first or second conventional configuration. Therefore, the knockout tank does not appear to be an effective technology at improving the cost-effective operation of the bioslurper system at Tyndall AFB. The dual drop tube configuration significantly reduced the average extractable TPH concentration in the seal tank water relative to the conventional configuration. The analytical results show that the extractable TPH concentration was not detected in the seal-tank water during the dual drop tube configuration test.

The knockout tank configuration test showed a decrease in the TPH concentration in the off-gas. The average decrease in the off-gas during the knockout tank configuration test was approximately 20% compared to the first conventional configuration test. The dual drop tube also appeared to reduce concentration of petroleum hydrocarbons in the off-gas from the bioslurper. There was an approximate 30% reduction in TPH in the off-gas during the dual drop tube configuration test compared to the first conventional configuration test.

The knockout tank did not provide reasonable separation of the LNAPL and the groundwater before the liquid ring pump, and relatively large volumes of floating solids were produced in the

extraction process. Additionally, the dual drop tube nearly eliminated the production of floating solids in the postpump-treatment equipment.

5.2.1.6 Data Assessment at NFD Point Molate, California

Due to the limited LNAPL recovery, several wells were used during the demonstration. The knockout tank was not tested due to limited LNAPL recovery and the limited effectiveness observed at other demonstrations. The first conventional and the dual drop tube configurations will be compared due to the similar LNAPL recovery rates measured during these two tests. These two tests were performed at the same well. During these two configurations, water was metered into the system because of low groundwater recovery. During the first conventional configuration test, water was metered in at approximately 2 gpm. This was considered excessive, so the rate was decreased to about 1 gpm during the dual drop tube configuration and the second conventional configuration.

The test results did indicate that the dual drop tube system was successful at reducing the TPH concentrations in the seal and process water. During operation at P86-13/14, TPH concentrations in the seal water were reduced by at least 97%. In addition, the TPH concentrations measured were corrected for the dilution caused by the greater bleed rate of tap water during the first conventional test. This correction resulted in a doubling of the TPH concentrations measured during the first conventional test. The reduction in the TPH concentration caused by the operation of the dual drop tube system would likely be greater if the TPH concentrations were also corrected for the LNAPL-recovery rates. In general, the greater the LNAPL-recovery rate, the greater the TPH concentrations in the seal and process water. However, the relationship between the LNAPL-recovery rate and the TPH concentrations is unknown, so the concentrations cannot be corrected. Figure 5-8 displays samples of the process water, seal water, and free-product recovered during the dual drop tube test.

The test results also indicated that the dual drop tube configuration was effective in reducing TPH concentrations in the off-gas stream. During the operation at well P86-13/14, TPH concentrations in the off-gas were reduced by 24%.

Floating solids were not a problem with well P86-13/14 due to the low recovery of LNAPL and groundwater.

5.2.1.7 Data Assessment at MCAS Cherry Point, North Carolina

LNAPL was not recovered during the first and second conventional configurations, while LNAPL was recovered during the dual drop tube test. The knockout tank configuration was not tested at this site due to its limited efficiency. It appears that the LNAPL-recovery rate was enhanced by the use of the dual drop tube system. This increase, however, is likely the result of the mixing of the LNAPL and water during conventional bioslurper operation and preventing the blending during dual drop tube operation. The blended LNAPL is carried through the aqueous process stream in a suspended form during conventional bioslurper operation. The groundwater recovery was similar through all three configurations.

Figure 5-8. Samples Of The Process Water, Seal Water, And Free-Product Recovered During The Dual Drop Tube Test

The dual drop tube system was effective at reducing the petroleum hydrocarbons in the aqueous stream from the bioslurper. The dual drop tube system reduced the TPH concentration by 95% in the seal-tank water.

A handheld meter measured off-gas concentrations from the stack during each configuration. The dual drop tube showed a decrease in off-gas TPH concentrations compared to the conventional configuration tests. The TPH concentrations were reduced by approximately 65%. These measurements were not confirmed by laboratory analysis of an off-gas sample taken by a summa canister.

During the conventional configurations, a milky emulsion was formed due to the blending of the LNAPL. The dual drop tube eliminated the production of the milky emulsion and floating solids during the extraction process.

5.2.1.8 Data Assessment at Hickam AFB, Hawaii

The demonstration data indicate that the bioslurper system was effective at removing LNAPL from the subsurface in both the conventional and dual drop tube configurations. A total of 289 gallons of LNAPL were removed from the site during the demonstration, and 114, 140, 35 gallons were removed during the first conventional, dual drop tube and second conventional tests, respectively. These data suggest that operation in the dual drop tube configuration was more effective at recovering LNAPL than the conventional configuration. However, this effect likely results from the ability to quantify more LNAPL during the dual drop tube operation rather than recovering more LNAPL (similar to the demonstration at MCAS Cherry Point). As LNAPL is extracted during the conventional configuration it is emulsified in the process water stream. Therefore, some of the recovered LNAPL passes through the system in a suspended form and cannot be quantified. Operation in the dual drop tube configuration prevents this emulsion formation and most of the recovered LNAPL can be quantified. The lower LNAPL recovery rate observed during the second conventional test is likely caused by depletion of LNAPL from the subsurface during earlier operations. The first conventional and dual drop tube tests were used for comparison purposes because the LNAPL and groundwater recovery rates were similar; therefore the potential for emulsification and volatilization would be similar.

The dual drop tube configuration was able to greatly reduce the TPH concentrations in the seal water of the bioslurper. Comparing the first conventional and the dual drop tube configurations, the dual drop tube configuration reduced the concentrations in the seal-tank water by 94%.

Additionally, the dual drop tube configuration was able to reduce the off-gas TPH emissions. The dual drop tube system reduced the TPH concentrations in the vapor stream by 22% relative to the first conventional configuration.

Some floating solids were formed when operating in the conventional configuration. The dual drop tube configuration reduced the production of floating solids and emulsions.

5.2.2 Data Assessment of the Long-Term Demonstration Site

The LNAPL recovery remained consistent throughout the demonstration except for the first conventional configuration which had double the gallons per day at 155 gpd than the rest of the demonstration which averaged 75 gpd. For comparison purposes, the prepump separations data will be compared to the second conventional configuration data because of the similar LNAPL recovery rates. The groundwater recovery remained relatively constant over the course of the demonstration. The average groundwater recovery rate was 2 gpm.

The prepump separation techniques reduced the TPH concentrations in the seal-tank water compared to the second conventional configuration. The average TPH concentration reduction when using the dual drop tube configuration was 98% compared to the second conventional configuration. The reduction did not seem to be dependent on the number of wells or the use of a surge tank. The knockout tank configuration had a TPH concentration reduction of 82% relative to the second conventional configuration.

The off-gas concentrations did not seem to be affected by the use of the prepump separation technologies. The second conventional configuration had the lowest TPH concentration for the

off-gas. The dual drop tube configuration and the knockout tank configurations had the same or higher TPH concentrations in the off-gas stream.

NAS Fallon did not seem to produce floating solids. The dual drop tube and the knockout tank configuration did reduce the formations of the milky emulsions.

6.0 Cost Assessment

6.1 Cost Performance

The assessment of performance costs is based primarily on the data collected during the long-term demonstration performed at NAS Fallon and data collected during full-scale bioslurper operation at Pembroke Park, Coastal Systems Station (CSS) Panama City, and Hickam AFB. During the demonstration at NAS Fallon, the bioslurper was operated for approximately 3.5 months in the conventional, dual drop tube and knockout tank configurations. Also, the system was connected to five wells throughout the operation in order to investigate the operation in a "full-scale" configuration. Aside from the addition of the prepump separation systems, the bioslurper system remained unaltered so an accurate side-by-side comparison of the O&M requirements could be made. Throughout the long-term demonstration the labor effort and activities performed were accurately recorded to evaluate the cost requirements. Additional cost data for bioslurper systems operating with postpump-treatment options (dissolved air flotation and clay/carbon) were generated from operation at other sites such as Pembroke Park and CSS Panama City. These sites were selected because alternative water treatment systems were used at the sites. Also, cost data from Hickam AFB provided information for using an internal combustion engine for treatment of the vapor discharge stream.

Table 6-1 contains the cost data for operating the system at an "average" LNAPL site. At this typical site, the LNAPL layer covers an area of 2 acres and the depth to water is 20 ft below ground surface. The soils at the site are composed of silts and sands. In addition, the operational time for the bioslurper is expected to be two years, and the system is appropriately sized (20-hp liquid ring pump, 30-ft well spacing, etc).

Table 6-1. Cost Data for Operating the System at an Average LNAPL Site

Bioslurper Operation with Manual Removal of Floating Solids	Costs	Bioslurper with DAF Unit for Post-pump treatment	Costs	Bioslurper with DDT for Pre-pump treatment	Costs
Capital Costs		**Capital Costs**		**Capital Costs**	
Bioslurper System	$62,000	Bioslurper System	$62,000	Bioslurper System	$62,000
Well Installation	$15,000	Well Installation	$15,000	Well Installation	$15,000
Additional Equipment	$0	DAF Units	$77,000	DDT for all Wells	$1,000
Operation & Maintenance		**Operation & Maintenance**		**Operation & Maintenance**	
Labor (Including Manual Removal of Floating Solids)	$68,000	Labor (Including Upkeep of DAF System)	$81,000	Labor (Including Adjustment to Dual Drop Tube)	$26,000
Chemicals	$0	Chemicals for DAF	$153,000	Chemicals	$0
Sludge and Waste Disposal	$20,000	Sludge and Waste Disposal	$20,000	Sludge and Waste Disposal	$0
Carbon Treatment	$120,000	Carbon Treatment	$20,000	Carbon Treatment	$20,000
Total	$285,000	**Total**	$428,000	**Total**	$124,000
Cost Savings	$143,000	**Cost Savings**	$0	**Cost Savings**	$304,000

This average site was selected to best estimate costs and to provide unit costs for cleanup. However, the systems that were operated at these demonstrations and used for comparison were conventional bioslurper systems that included additional equipment for aqueous and vapor discharge treatment. Therefore, the table has been constructed to display the capability of reducing costs in these areas with the dual drop tube system. The majority of the bioslurper structure remains the same between three configurations: conventional (with O&M for handling the floating solids and off-site disposal of floating solids), conventional with dissolved air flotation (for enhanced oil/water separation) and off-site disposal of the floating solids, and bioslurper operation with the dual drop tube system.

The data in Table 6-1 display the costs for operating the bioslurper system at the average site in the three operational configurations and presents the cost savings with the dual drop tube system. Again, these data represent costs over the entire LNAPL-recovery effort (i.e., two years). Because the basic system is the same for the three operational configurations, the bioslurper costs are the same for each configuration. In addition the cost for well installation is the same because each of the configurations have the same radius of influence and thus require the same number of wells to cover the site. The additional capital equipment includes pre- and postpump oil/water separation and water treatment equipment (e.g., dual drop tube piping for prepump treatment an dissolved air flotation equipment). The labor rates for O&M have been standardized to provide the same labor rate. In addition to increased labor requirements to operate the dissolved air flotation system, relatively expensive chemicals, such as polymers, are required to operate the DAF system. While the DAF system significantly reduces the hydrocarbon concentrations in the discharge water, floating solids and sludge are still produced. This sludge generally needs to be disposed off-site.

These data indicate that operation of the bioslurper system in the dual drop tube configuration would save approximately $304,000 compared to operation with a DAF unit (and $161,000 with conventional operation, manual removal of floating solids, and treatment of the water with activated carbon) over the duration of the LNAPL-recovery effort. The additional cost of the conventional bioslurper operation results from the added labor required to remove the floating solids from the bioslurper system and from the off-site disposal of these floating solids. Because floating solids are not produced during operation with the dual drop tube system, these costs have not been included. The additional cost calculated for conventional operation with DAF for treatment of the aqueous stream results from the high capital cost of the equipment and the cost for off-site disposal of the floating solids removed with the DAF unit. The cost to produce dual drop tube systems for all of the wells at the site would be very low (approximately $1,000) because the components of the dual drop tube system are PVC piping.

7.0 Regulatory Issues

Regulatory acceptance of the dual drop tube and knockout tank technologies essentially would be the same as that for the conventional bioslurper technology. However, acceptance by the regulators would likely be much easier when the prepump separation systems are installed on the bioslurper system because TPH discharge levels would be much lower when the prepump separation systems are in place. The conventional bioslurper system is well accepted by regulators, and has been implemented at over 200 sites across the United States, both for the DoD and the private sector. During the demonstrations conducted for ESTCP, regulatory acceptance of the bioslurper technology and the prepump separation systems was universal – at every site where regulatory approval was requested, it was granted. It is believed that the bioslurper technology is the standard method for LNAPL recovery, and the prepump separation systems will enhance the capability of the bioslurper systems.

8.0 Technology Implementation

8.1 DoD Need

As was stated in Section 7, the prepump separation systems will likely be used with most bioslurper systems in the future. It has been estimated that there are thousands of LNAPL-contaminated sites in the DoD that require remediation, and bioslurper systems have been installed at approximately 100 of these sites. It would be estimated that the average LNAPL-contaminated site would be approximately 2 acres in area and would contain approximately 10,000 gallons of spilled fuel. In the private sector, there are likely thousands of sites that require remediation; however, many of these are relatively small sites and the use of a bioslurper may not be warranted due to the high cost.

8.2 Transition

The prepump separation systems likely will require only minimum testing in the future to further evaluate their effectiveness at sites with high-volatility fuels (for effectiveness at reducing TPH in the off-gas stream) and at sites with significant tidal fluctuations. Testing of the systems primarily would be used to fill data gaps in the research of the technologies and to determine if improvement can be made while operating under these conditions because the systems have been demonstrated to be functional at sites with these conditions. During the ESTCP-funded demonstrations, the prepump separation systems were tested at sites with a variety of geologic, hydrogeologic and contaminant conditions; therefore, there is confidence that the systems will operate effectively at most sites. It is recommended that pilot-scale testing be performed at each proposed test site so proper sizing of the equipment (drop tubes, knockout tanks, etc.) can be done. Additionally, pilot-scale testing will provide off-gas and aqueous discharge data that may be used when seeking regulatory approval of a full-scale LNAPL-recovery system.

The prepump separation technologies are at a state where they are ready to be used throughout the DoD and in the private sector. The systems are relatively simple and effective to use and upgrading existing bioslurper systems with the prepump separation systems should be a relatively easy and inexpensive operation to perform. The technology has been and should continue to be transferred through remediation conferences, peer-reviewed articles, and environmental literature in the next one to two years. In addition, a user's guide for the bioslurper technology is being modified to include data from the testing of the prepump separation technologies and will describe methods for using the prepump separation systems. Because the prepump separation systems are constructed of off-the-shelf materials, it is not believed that procurement guidance will be needed.

9.0 Lessons Learned

The efficiency of the prepump separation configurations (the knockout tank and the dual drop tube) for reducing the petroleum hydrocarbon in the aqueous and vapor streams and reducing the production of floating solids was tested at eight Department of Defense facilities. The eight sites were selected to represent different types of geology, hydrogeology, and contaminants.

The results from the demonstrations indicate that the dual drop tube configuration works well at a variety of sites that include tidal influence, varied geologic conditions (sandy to clay-rich soils), varied hydrogeologic conditions (groundwater depth from 3 ft to 50 ft), and varied LNAPL types (JP-4 to Bunker) and thickness (1.0 ft to 3.5 ft).

The results have shown that the dual drop tube configuration is very effective at reducing the TPH concentrations in the aqueous and vapor effluent. It has also shown almost complete elimination of floating solids. At NCBC Davisville, the water samples were taken after the oil/water separator that skewed the results. No reduction in the effluent water was shown, which we believe is due partly to the sampling location. In the other seven sites, the TPH concentration of the seal-tank water was reduced by 98% compared to a conventional bioslurper.

The dual drop tube configuration works moderately well in reducing the TPH concentration of the off-gas. The average reduction at the eight sites in the TPH concentration of the off-gas was 37% compared to a conventional bioslurper. The dual drop tube configuration seems to work better at reducing the TPH concentration of the off-gas with the higher volatility fuel.

The dual drop tube configuration did not affect the recovery of the LNAPL relative to operation in the conventional configuration. In general, the LNAPL recovery rates decreased throughout the demonstration, but did not significantly decrease when operating in the dual drop tube configuration. In addition, the dual drop tube configuration did not appear to alter the groundwater recovery rate.

The dual drop tube configuration is cost-effective. The capital equipment costs and the O&M costs are essentially the same as the operation of the conventional configuration with no downstream treatment of the aqueous or vapor streams. The dual drop tube can be used on existing wells with a 2- to 6-inch diameter. The 1-inch PVC groundwater/soil gas drop tube with the ¼-inch stainless steel fuel drop tube seems to work the best with the fuel drop tube approximately raised ¼-inch above the groundwater/soil gas drop tube.

Some future work and recommendations are that the appropriate size of the liquid fuel trap is important. The size of the liquid fuel trap needs to accommodate the amount of LNAPL recovery, to minimize the amount of labor needed for O&M. In addition, the configuration with the 1-inch groundwater/soil-gas drop tube with the ¼-inch LNAPL drop tube appears to work best, though modifications may be needed if the groundwater recovery rates are low and LNAPL recovery rates are high. The fuel isolation sleeve that extends a foot above and below the oil/water interface works best, though modifications may be needed at sites with insufficient groundwater extraction rates, deep wells, or those with rapidly fluctuating water tables.

The aboveground prepump knockout tank separators performed less efficiently than the dual drop tube configuration, probably due to periodic failure to completely remove all LNAPL and emulsions from the water phase. The knockout tank technology was only performed at five of the sites. Of the three sites where the knockout tank was not performed, two had little LNAPL recovery and the third site had a tight time constraint which made us exclude the knockout tank test.

At half the sites, there was a reduction in the production of the floating solids. The average reduction in the TPH concentration of the seal-tank water was 24% compared to the conventional configuration. At NCBC Davisville, no reduction in the effluent water was shown as the water was sampled after the oil/water separator. The results from the knockout tank configuration demonstrate an average reduction in the TPH concentration of the off-gas of 22% compared to the conventional configuration.

The knockout tank configuration did not affect the recovery of the LNAPL relative to operation in the conventional configuration. In general, the LNAPL recovery rates decreased throughout the demonstration, but did not significantly decrease when operating in the knockout tank configuration. In addition, the knockout tank configuration did not appear to alter the groundwater recovery rate.

The knockout tank configuration had essentially the same capital costs and O&M costs as the operation of the conventional configuration with no downstream treatment of the aqueous or vapor streams. The knockout tank configuration is less complicated than the dual drop tube.

10.0 References

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